Scanning Electron Microscopy (SEM)

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Learning Objectives

- To describe basic principles of Scanning Electron Microscopy techniques for microelectronic device failure analysis

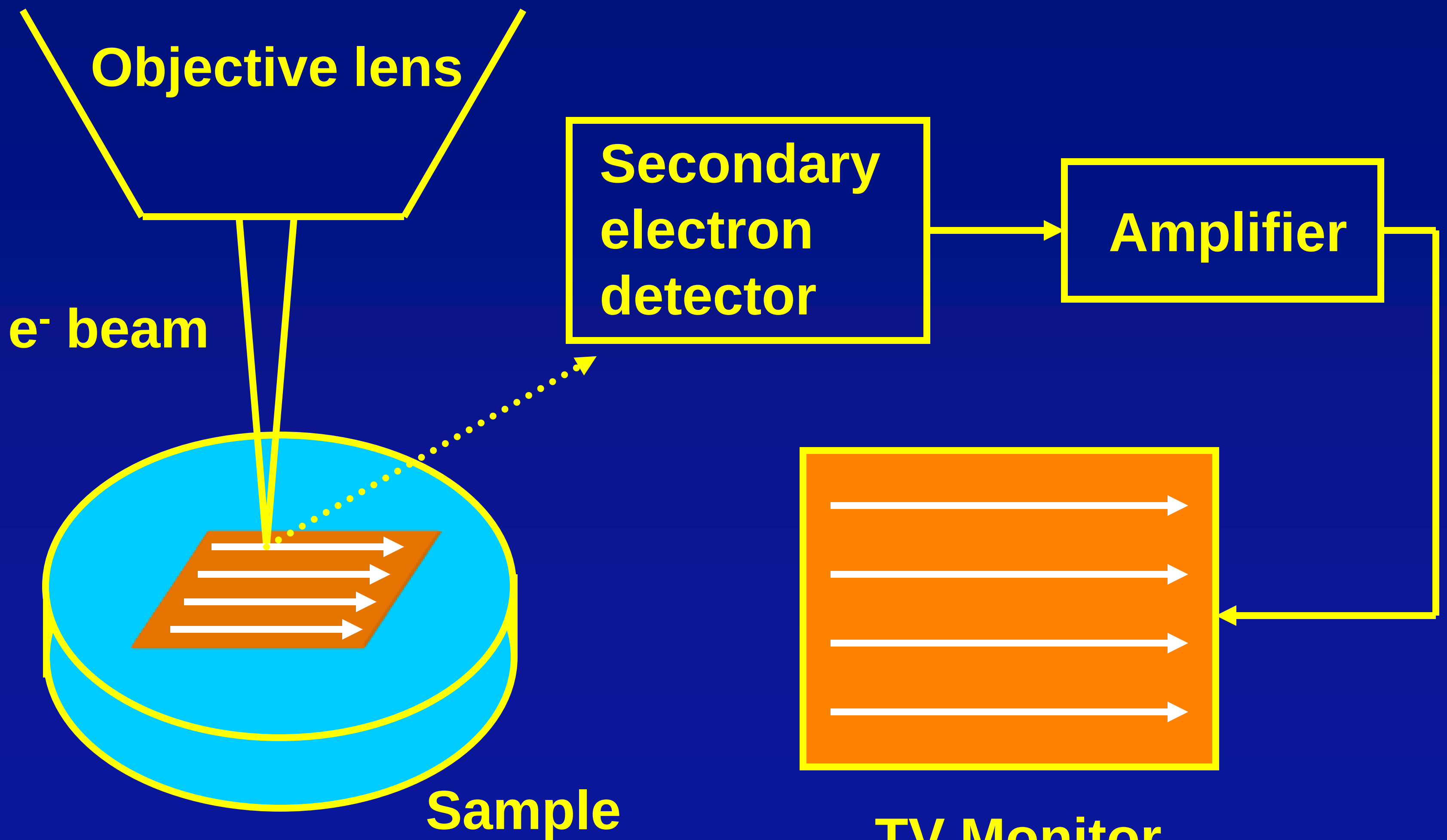
Outline

- Fundamental theory of SEM imaging and analysis
- Practical tips for getting a good SEM image
- Recent developments and new features for SEM of semiconductors

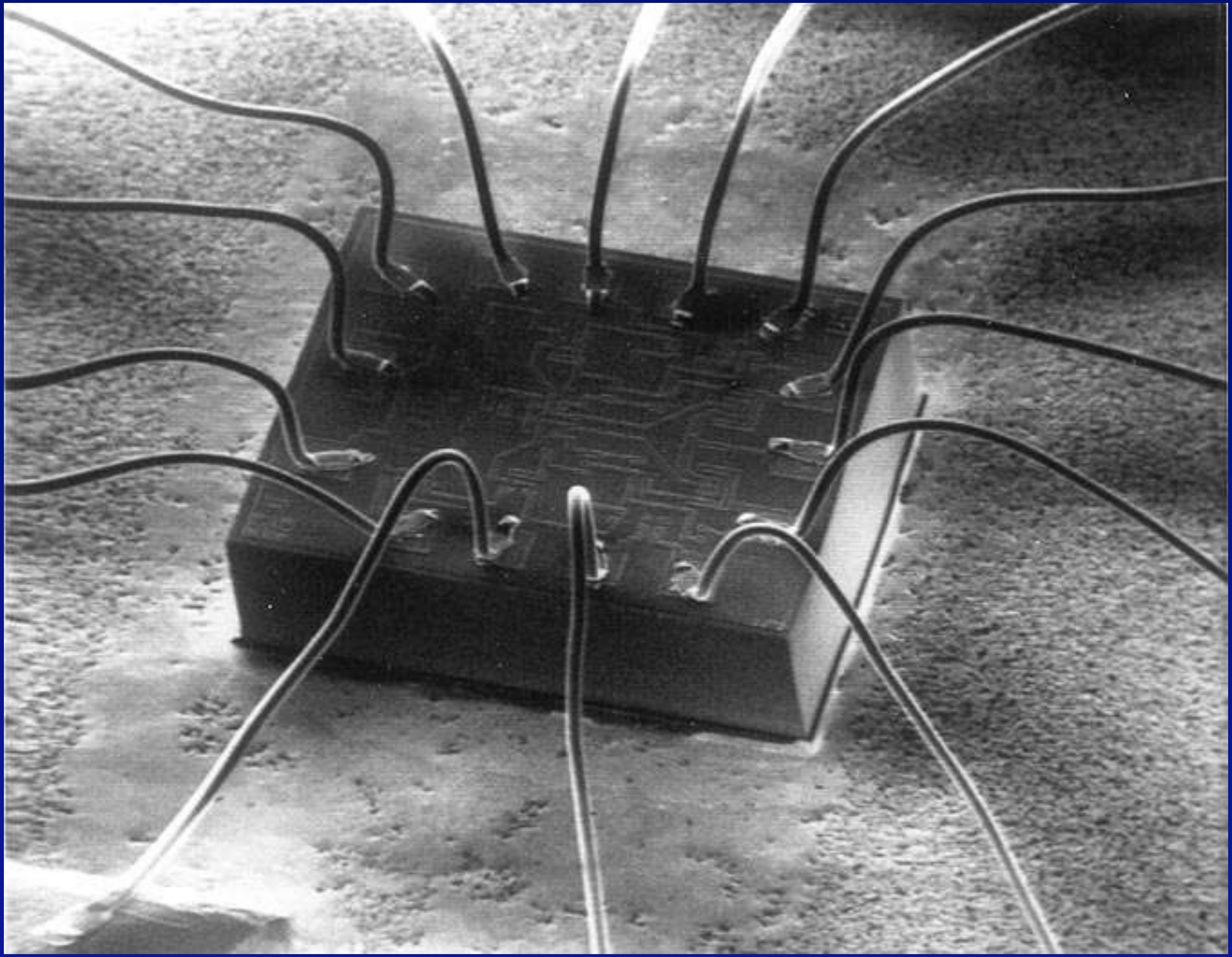
SEM vs. optical microscopy

SEM	Optical
High resolution (few nm)	Resolution ~ $\lambda/2$ ~ 250 nm
Large depth of field	Very shallow depth of field
X-ray elemental analysis	Color, phase contrast
	Bright field / dark field
Requires vacuum	No vacuum
Best on conductive samples	conductive or insulating
Poor TV rate imaging	Live image
Low contrast on defects	High contrast from defects
Difficult to navigate	Easy to navigate
May damage devices	Dielectrics are transparent

SEM principles



Sample SEM image



200 μm ——— **Mag = 50 x**

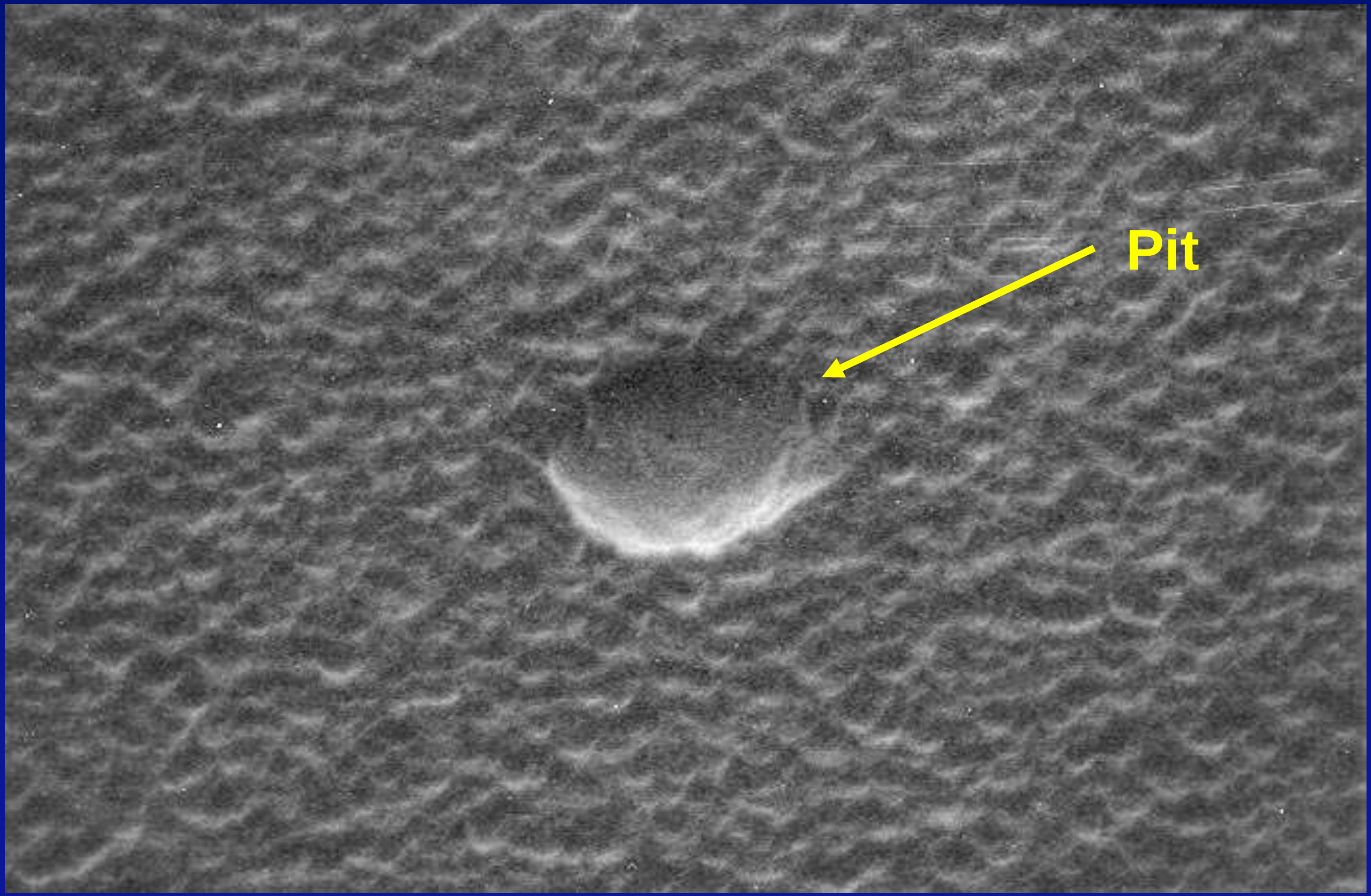
Scanning principles

The image perspective is as if you are looking down the column

The detector provides an apparent “source of illumination” to the image

The image should always be viewed with the detector at the top

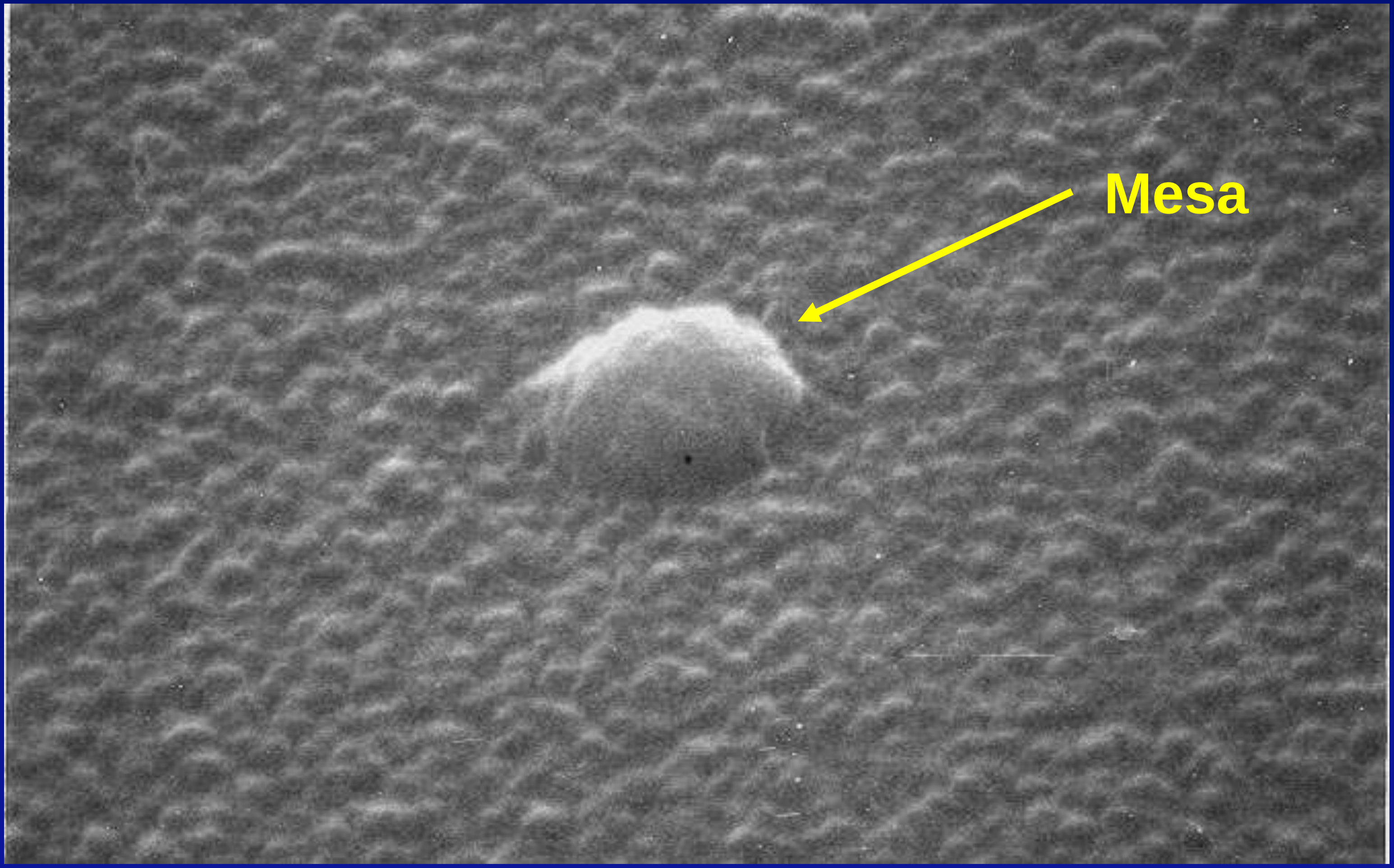
Deceptive images



1 μm

Mag = 30,000 x

Deceptive images

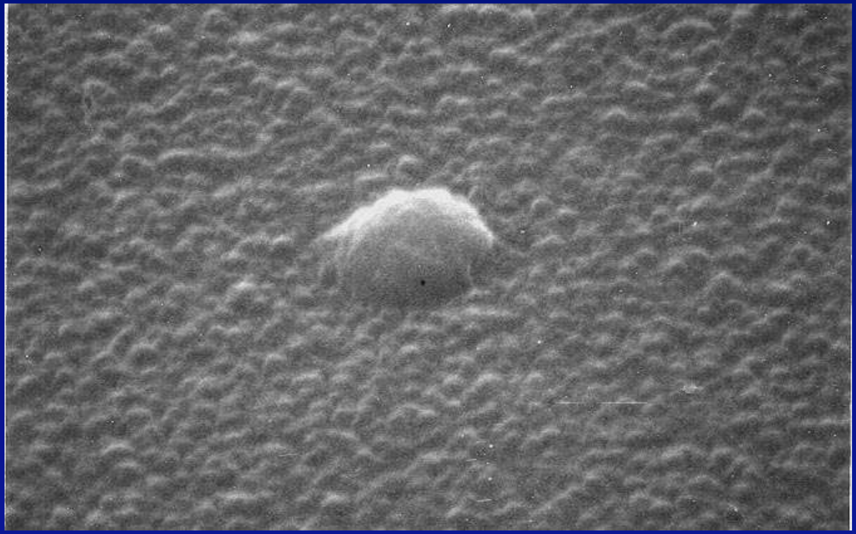


1 μm

Mag = 30,000 x

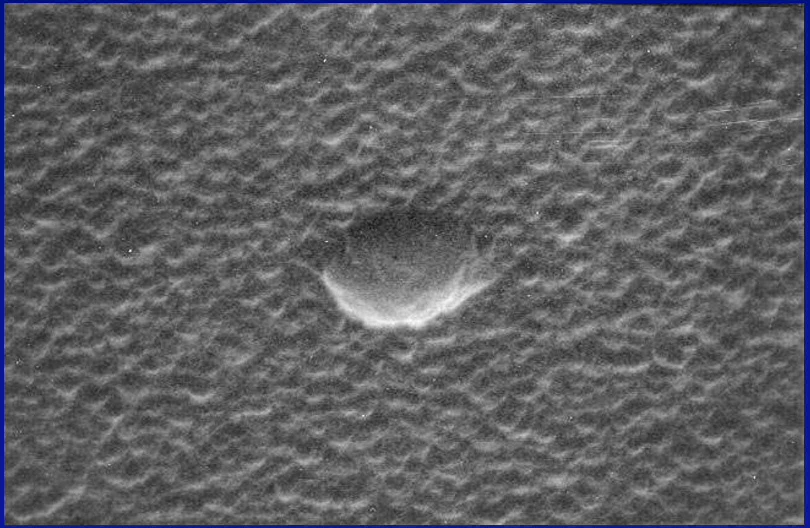
Deceptive images

Detector at top (correct image)



1 μm ——— **Mag = 30,000 x**

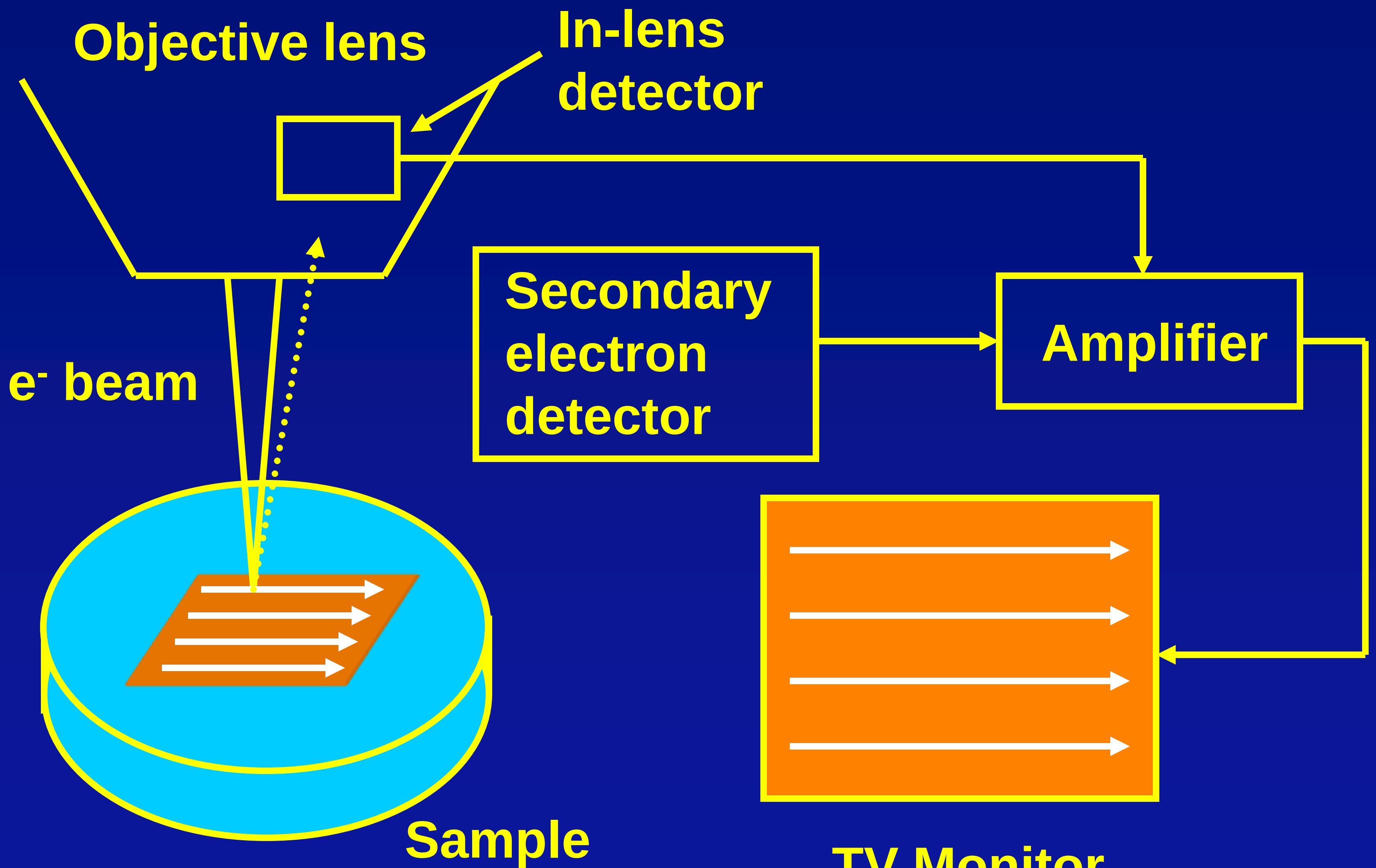
Detector at bottom



1 μm ——— **Mag = 30,000 x**

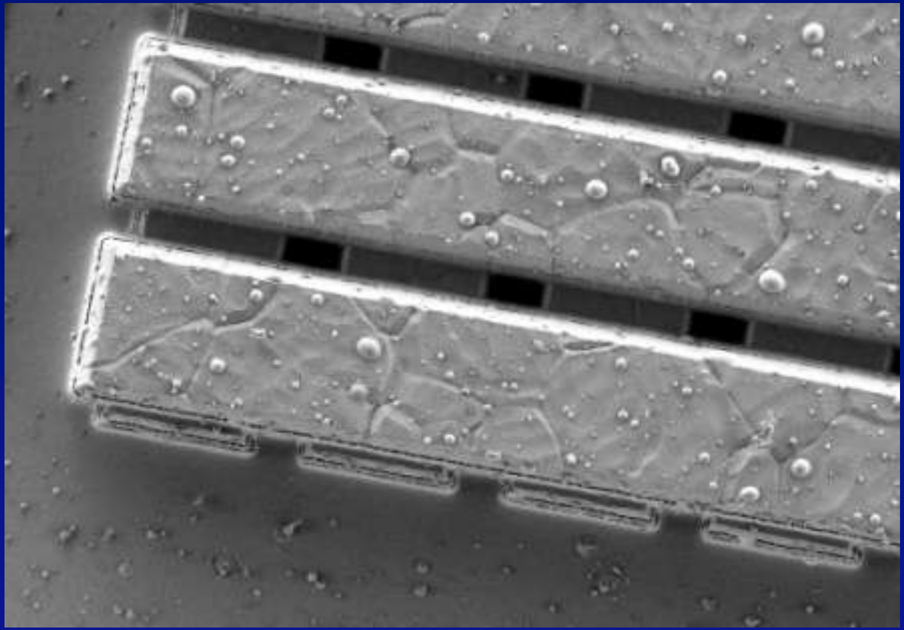
These are images of the same object!

In-lens secondary electron detector



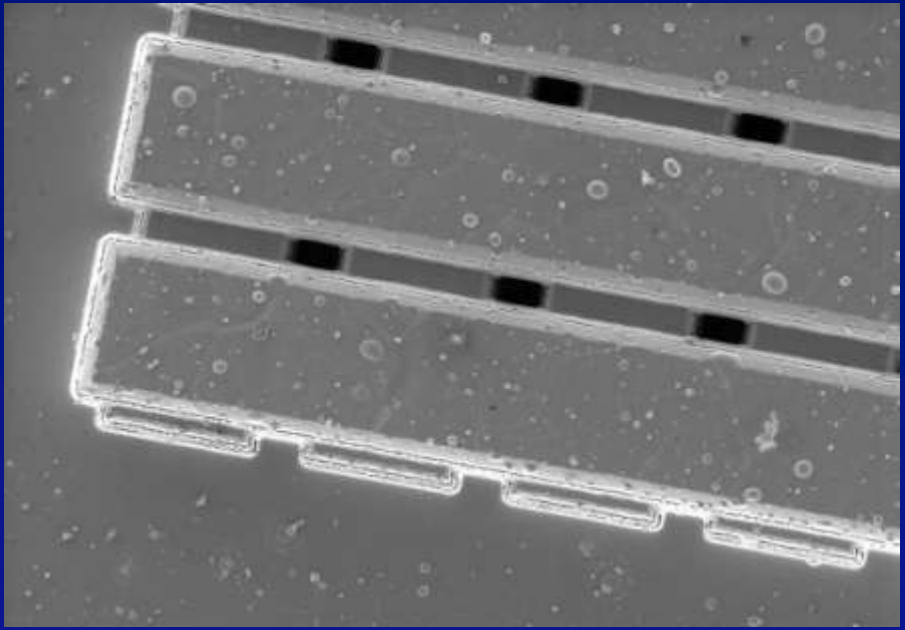
Secondary electron detectors

In-chamber detector



2 μm — **Mag = 5,000 x**

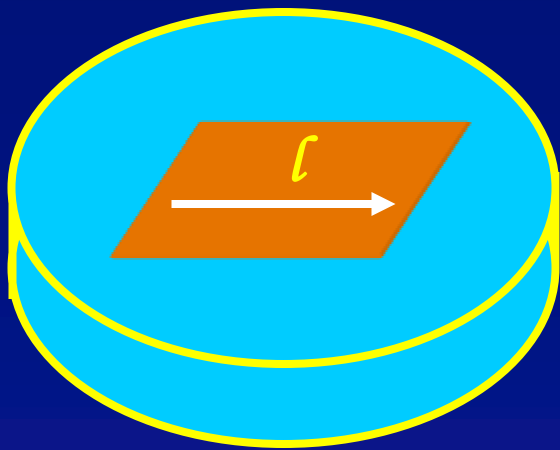
In-lens detector



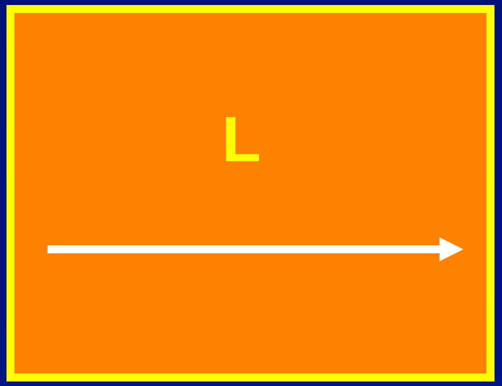
2 μm — **Mag = 5,000 x**

In-lens detector: Less topography, reduced charging (?), better signal from deep holes

Magnification



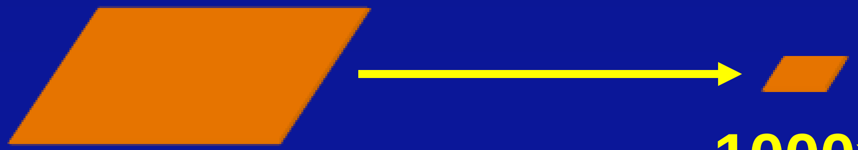
Sample



TV Monitor

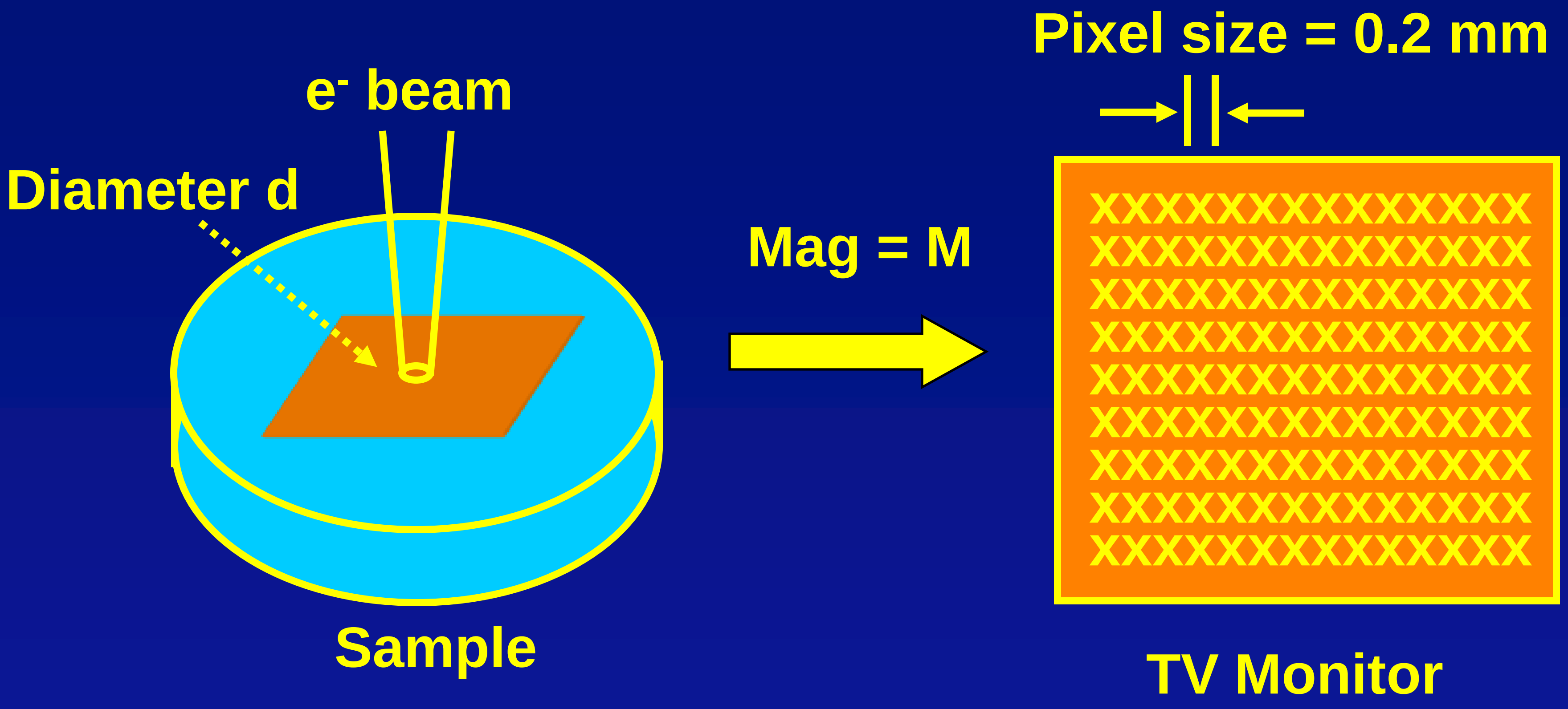
$$\text{Magnification} = \frac{L}{\ell}$$

To increase magnification, decrease the raster area



100x **1000x**

Maximum useful magnification



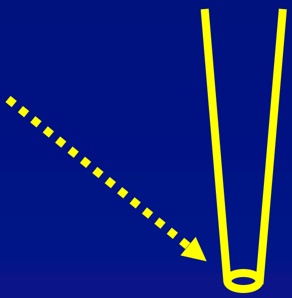
Beam diameter d when translated to the monitor has diameter d*M

Maximum useful magnification

Image in sharp focus

$d * M \leq 0.2$ mm

d * M

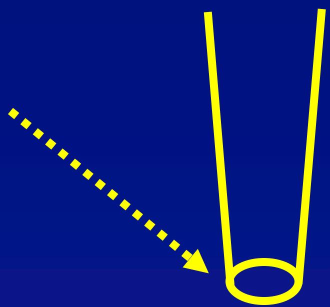


xxxxxxxxxxxxxx

Image not in sharp focus

$d * M > 0.2$ mm

d * M

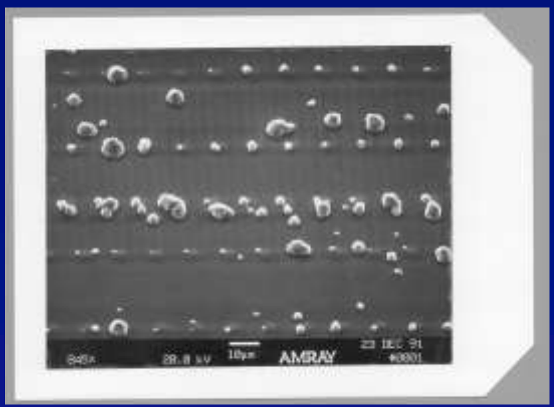


xxxxxxxxxxxxxx

$$M_{max} = 0.2 \text{ mm} / d$$

For d = 5 nm, the maximum useful mag is 40,000 x

Polaroid Mag v.s. Screen Mag



Polaroid Photo
3.5" x 4.5"
(9 cm x 11.5 cm)

Video Monitor

Digital Images

Computer Monitor

Proceeding from the 26[th] International Symposium for Testing and Failure Analysis, 12-16 November, 2000, Bellevue, Washington

Forensic Microscopy in the Failure Analysis Laboratory

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Abstract

Optical microscopy techniques used by forensic analysts are shown to have application to failure analysis problems. Proper set up of the optical microscope is reviewed, including the correct use of the field diaphragm and the aperture diaphragm. Polarized light microscopy, bright and dark field methods, refractive index liquids, and a particle reference atlas are used to identify contamination found on semiconductor products.

845X 20.0 kV 10µm AMRAY 23 DEC 91 #0001

A survey of the microelectronics failure analysis literature finds very few publications [1,2] on optical microscopy. International Reliability Physics Symposium (IRPS) Proceedings and Tutorials from 1988 to 2000 and International Symposium on Testing and Failure Analysis (ISTFA) proceedings from 1983 to 1999 contain almost no material specifically on optical microscopy. Some failure analysis engineers are poorly trained in optical microscopy and do not take full advantage of all the features of their microscopes. Optical microscopes are often under rated, perhaps because they are not expensive or "high tech". However, a simple and inexpensive technique such as polarized light microscopy can quickly and non-destructively identify particles that in some cases are difficult to identify by other methods. Furthermore, polarized light microscopy is excellently suited to compare contaminant particles with alternative sources of the contamination.

Experimental

The Art of Microscopy

Microscopy is the interpretive use of microscopes to provide specific information about a sample. [3] A basic understanding of microscope operation is necessary to achieve a good image, but the microscopist must also know how to use the instrument to display the particular features of interest in a given sample. There is not necessarily a "best" illumination, magnification, focus, or diaphragm setting for a given sample, it depends on what feature of the sample the microscopist wishes to emphasize.

Optical microscopes can be used in either transmission or reflection mode, i.e. the illumination can be from below and proceed through the specimen, or it can be from above and reflect off the specimen. Forensic microscopists typically use transmitted light to examine particles and fibers, while microelectronics failure analysts typically use reflected light to examine particles adhering to wafers or electronic components. However, in both modes the optical path will proceed through similar optical elements and techniques such as polarized light, dark field, and immersion lenses can be used. For this investigation, samples were examined with a Reichert Zetopan equipped for polarized light examination in transmitted, reflected, or mixed illumination mode. Some samples were also examined using a Leitz Ergolux without polarizers. The basic design of optical microscopes is discussed in many references [4,5] and will not be reviewed here.

Diaphragm Settings

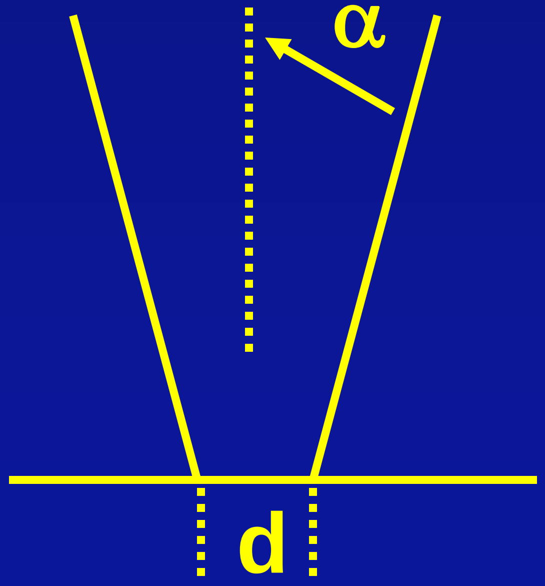
Optical microscopes (in either reflection or transmission mode) will typically have at least two diaphragms in the optical path. The field diaphragm is placed in a conjugal focal plane, and thus produces

What is the true mag?

***Always* use a micron marker**

Brightness

$$\text{Brightness} = \frac{\text{current}}{\text{area x solid angle}} = \frac{4\,i}{\Pi^2 \;\; d^2 \;\; \alpha^2}$$



i = beam current

d = beam diameter

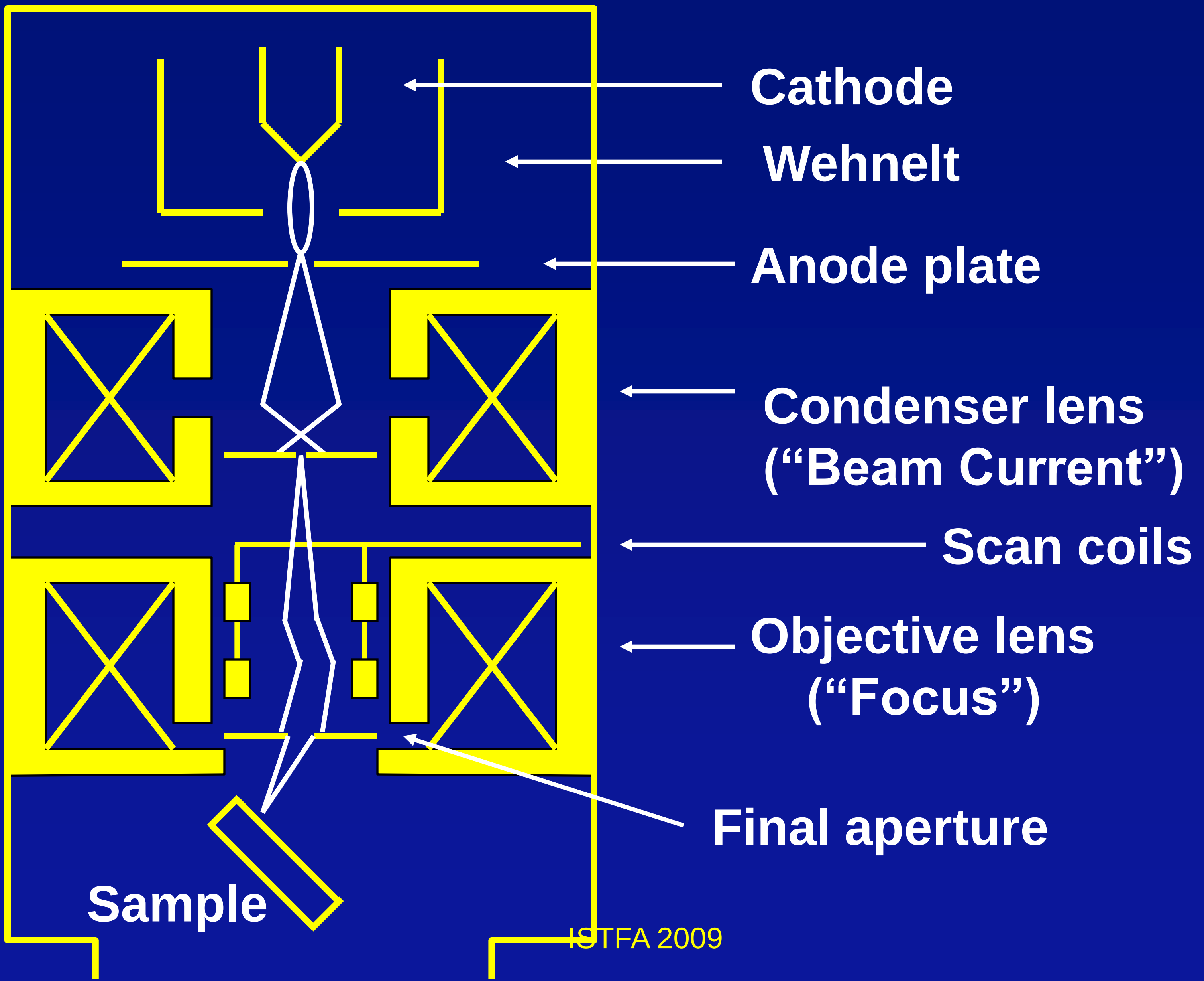
α = convergence angle

π = Pi ~ 3.14

SEM Cathode Comparison

Source:	Tungsten	LaB_6	Schottky Field Emission
Vacuum: (torr)	10^{-5}	10^{-7}	10^{-8}
Brightness: ($A/cm^2 \cdot sr$)	10^{+5}	10^{+6}	10^{+8}
Resolution:	10 nm	5 nm	1 nm
Lifetime (hours)	40-100	200-1000	>1000

SEM column


Cathode
Wehnelt
Anode plate
Condenser lens
("Beam Current")
Scan coils
Objective lens
("Focus")
Final aperture
Sample

Effect of lenses and apertures

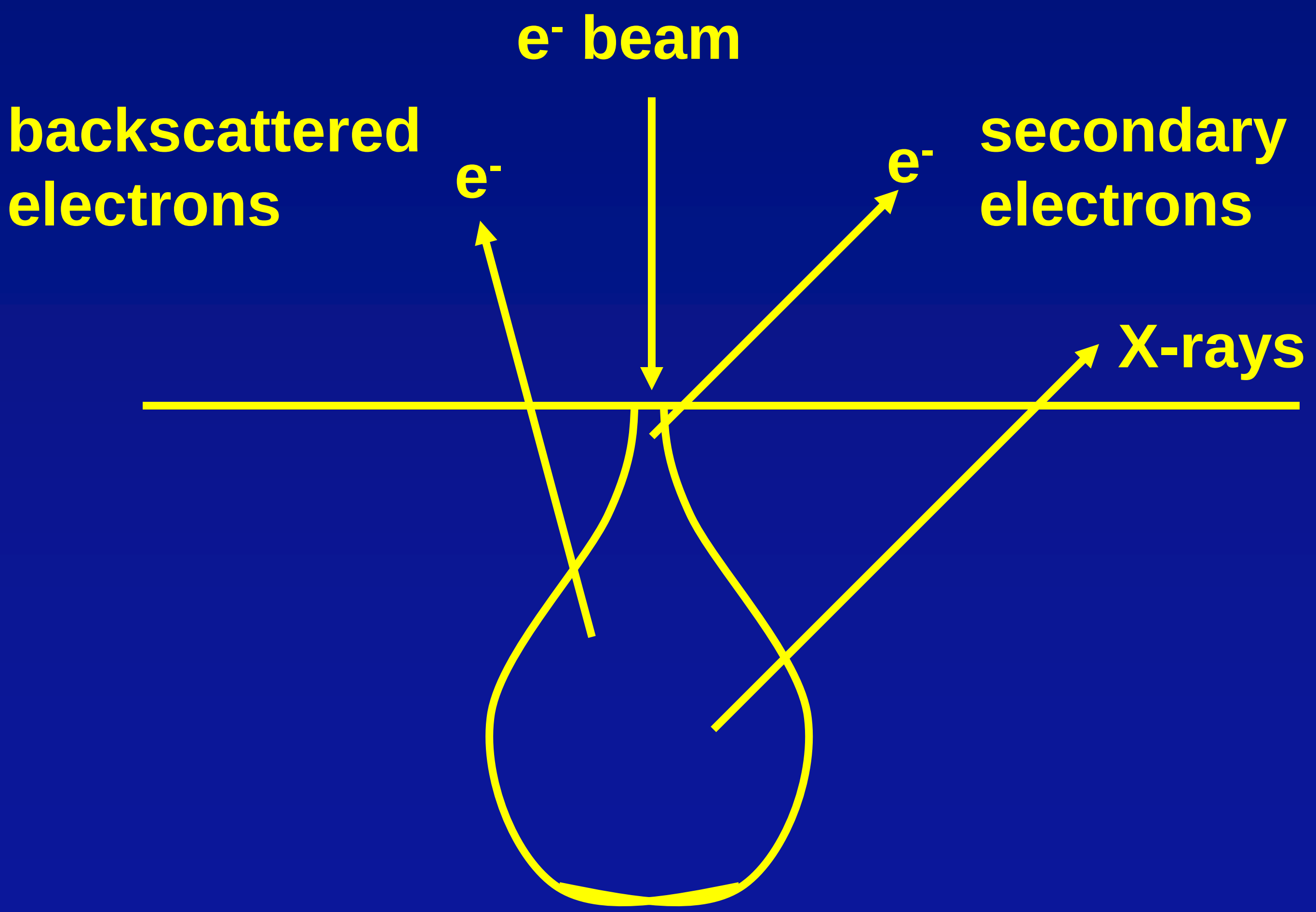
$$\text{Brightness} = \frac{4\,i}{\Pi^2 \quad d^2 \quad \alpha^2}$$

Lenses decrease d but increase α

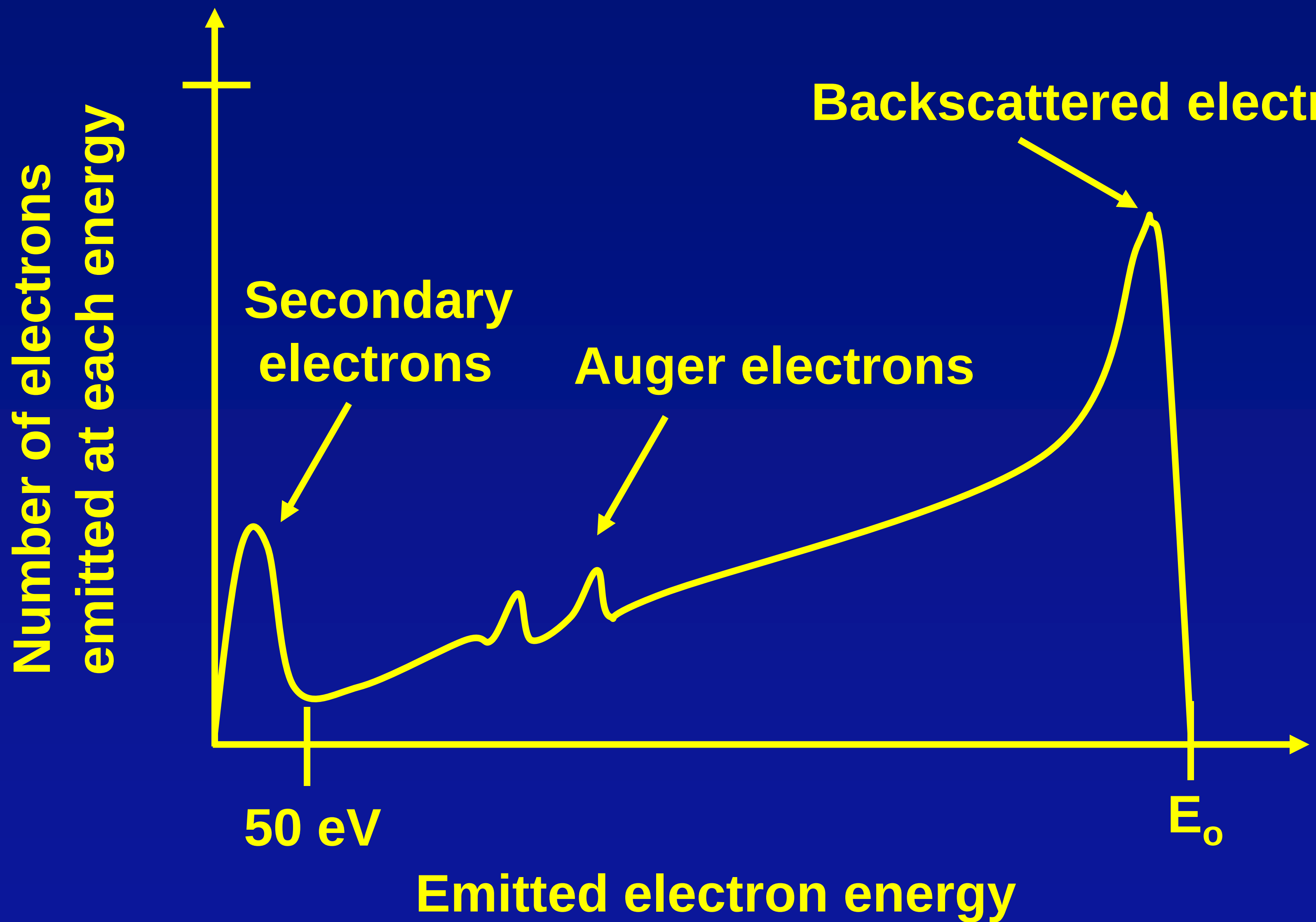
Apertures decrease α but also decrease i

We wish to have small d, small α, large i

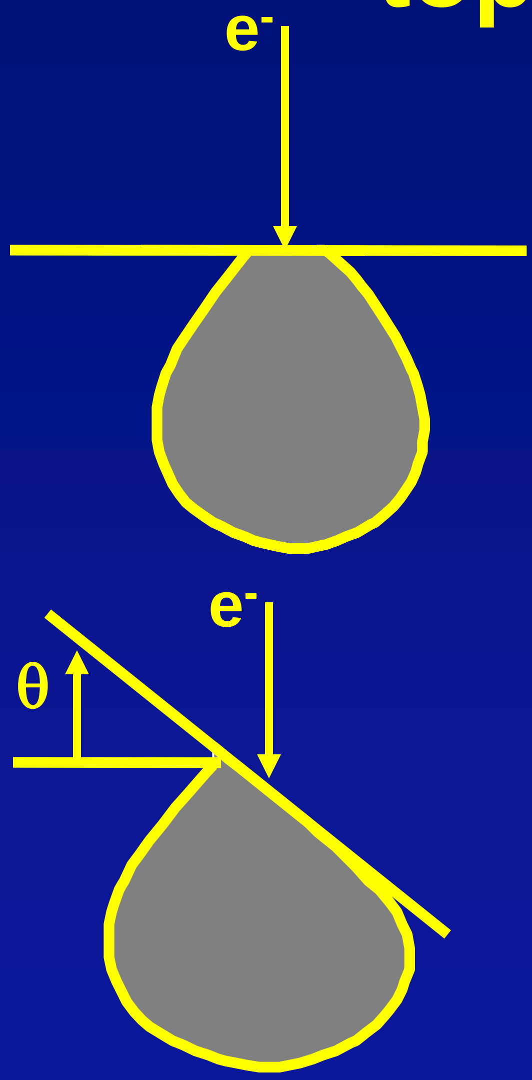
Electron Beam-Sample Interaction Products

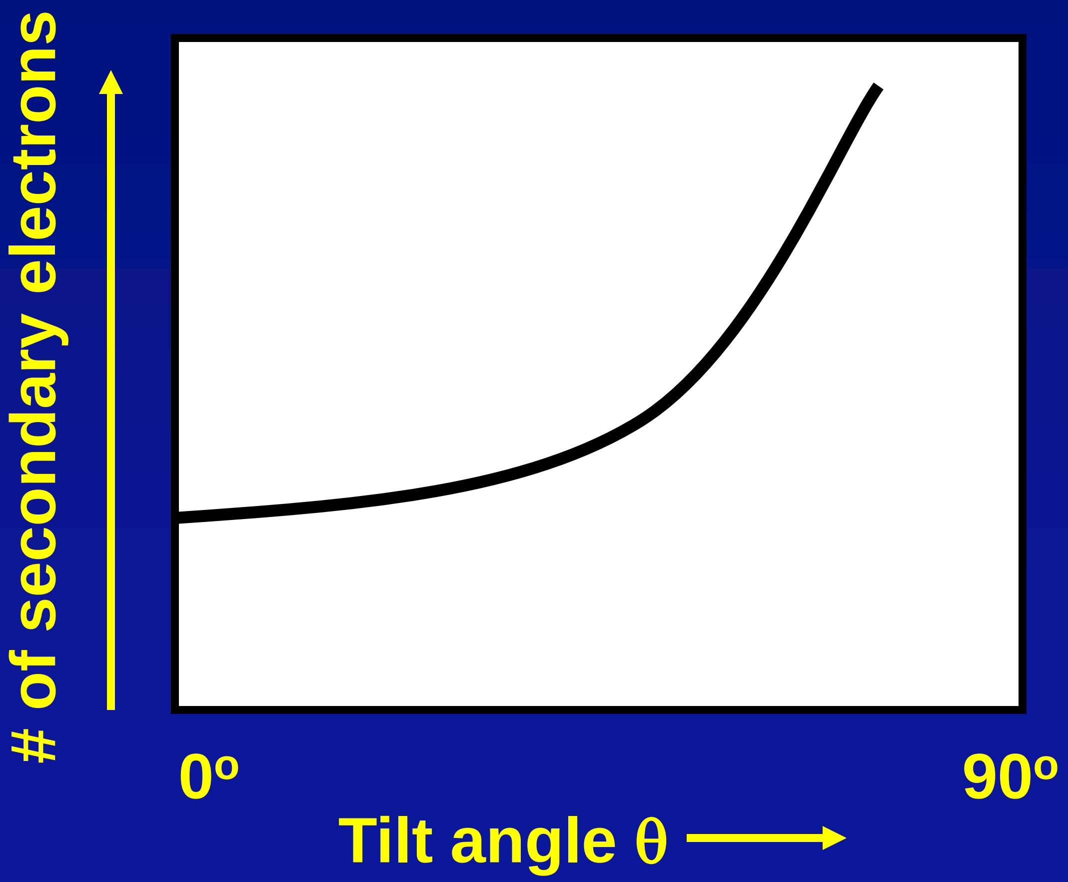


Electron energy spectrum



Secondary electrons: topography contrast

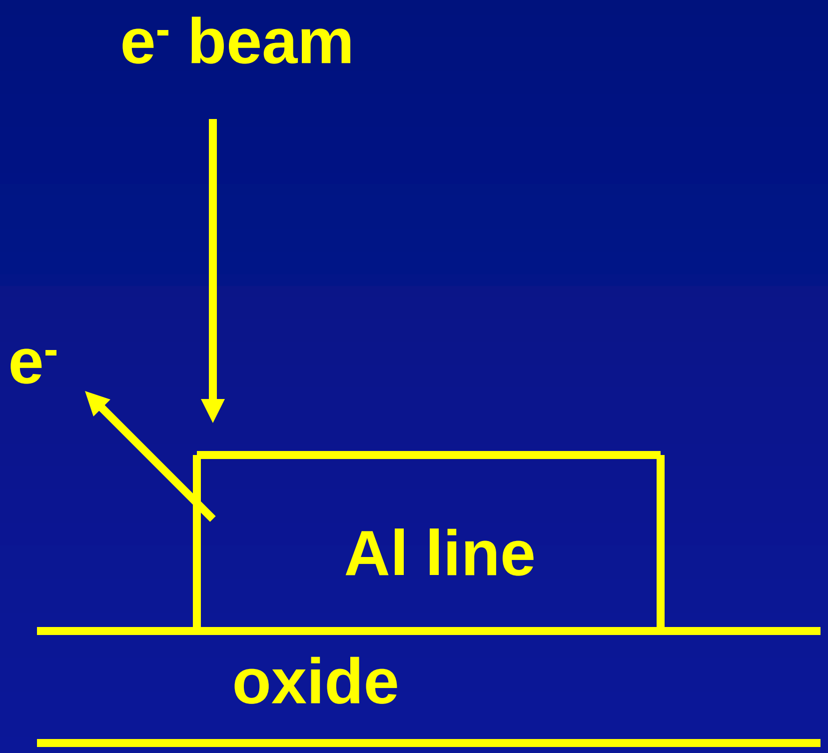




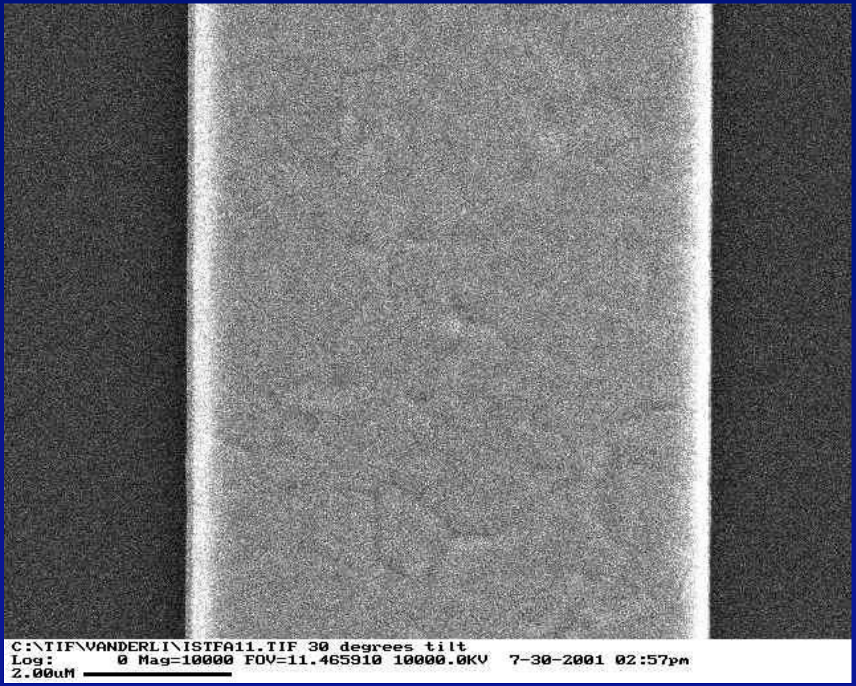
Secondary electrons: material contrast

Secondary electron coefficient ~ 0.1 for most materials
Exceptions: Carbon ~ 0.05
Gold ~ 0.2
Secondary electron coefficient strongly depends on surface roughness, sample cleanliness, tilt angle

Edge brightness



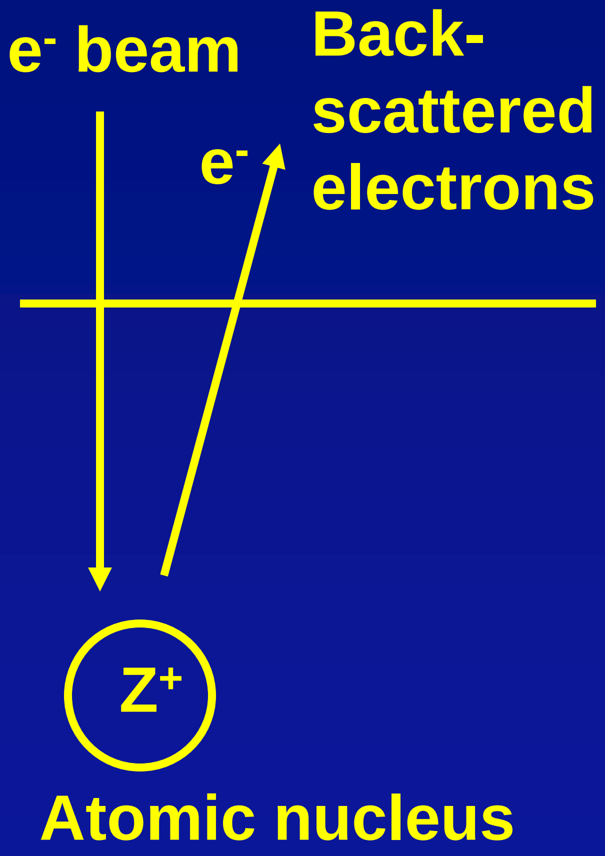
X-section of sample

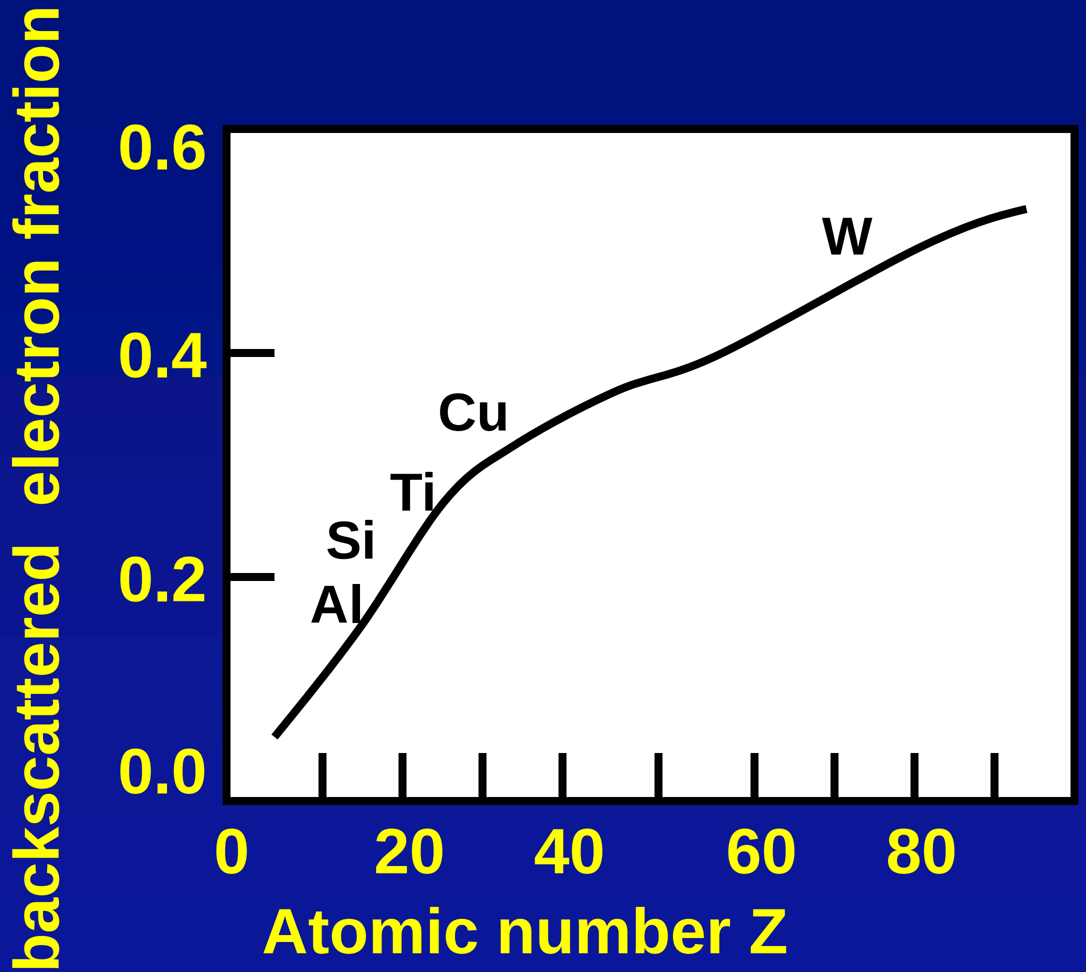


2 μm ——

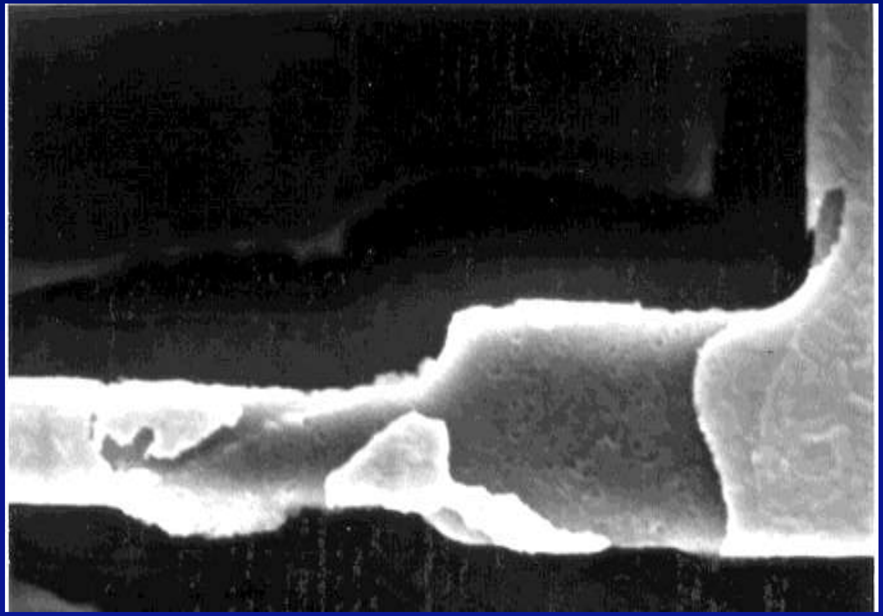
Mag = 10,000 x

Backscatter: atomic number contrast





Secondary vs. Backscatter imaging



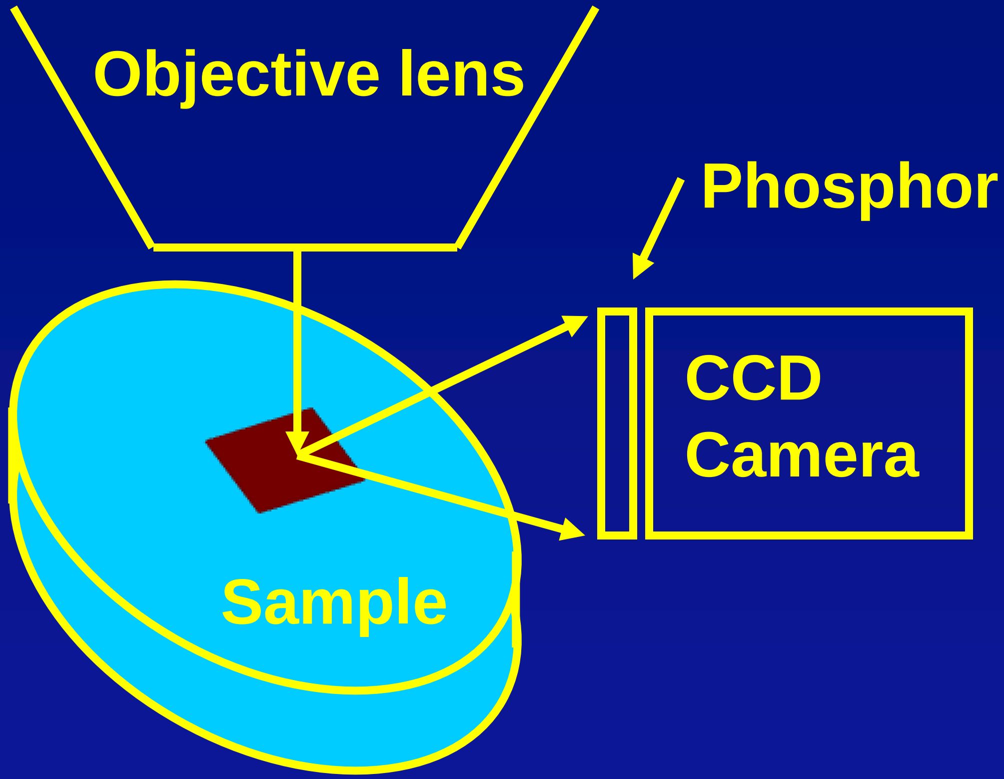
2 μm —— Mag = 6,000 x

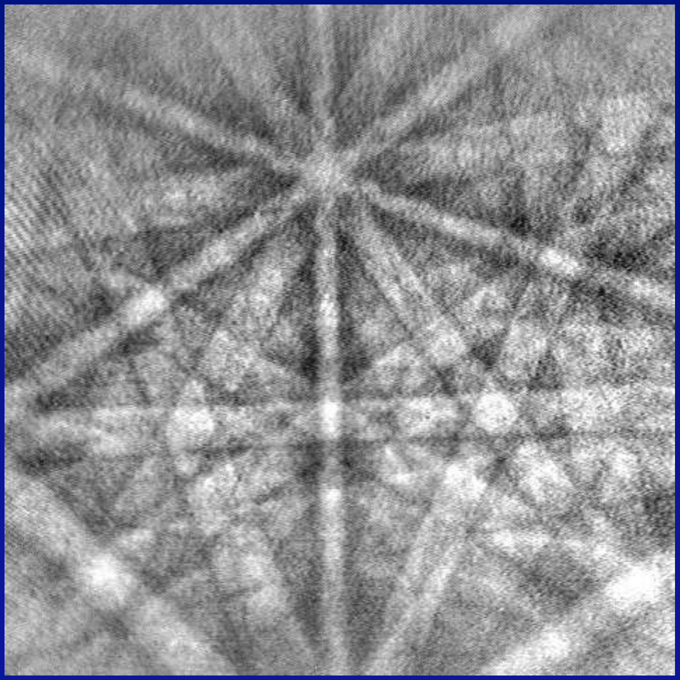
Secondary electron image

2 μm —— Mag = 6,000 x

Backscattered electron image

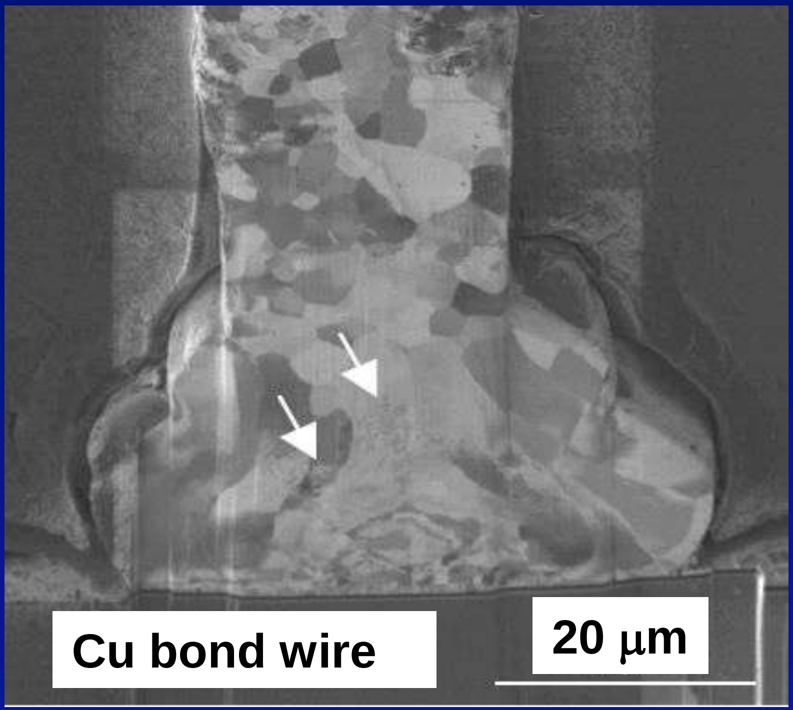
Electron back-scatter diffraction (EBSD)



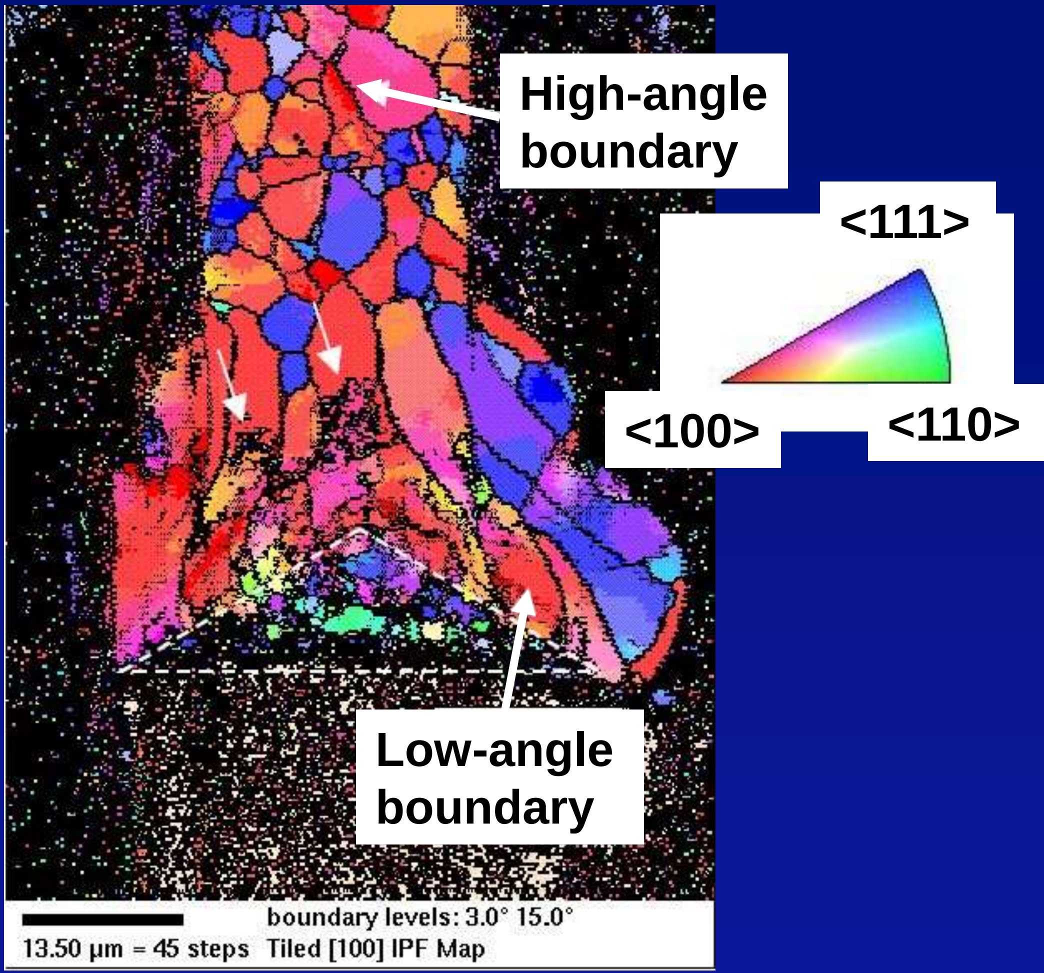


EBSD Pattern

Orientation Imaging Microscopy (OIM)



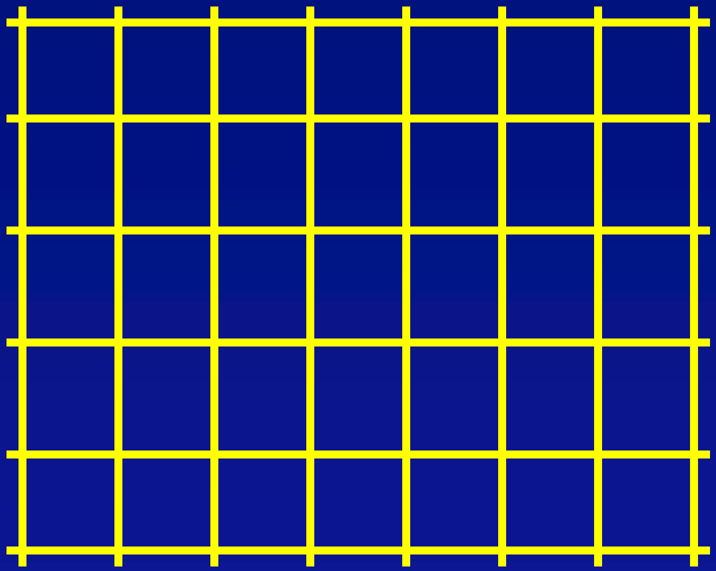
FIB image



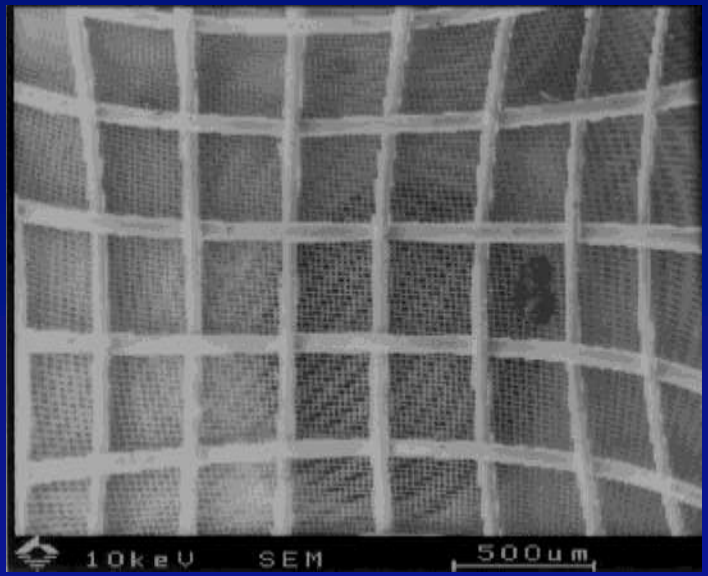
OIM image

Ratchev, Carbonell, Ho, Bender, De Wolf, Verlinden, Proceedings ISTFA 2002, p. 61-66.

Pincushion distortion



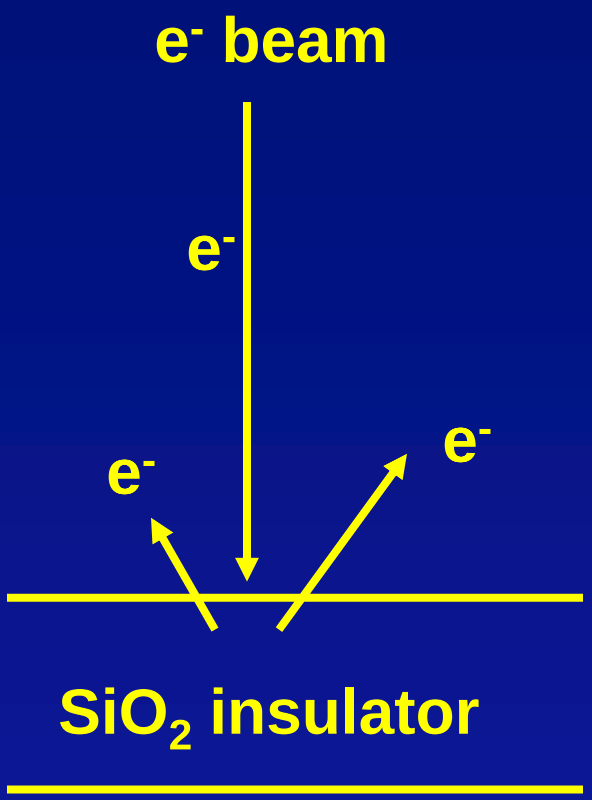
SEM Grid
(true appearance)

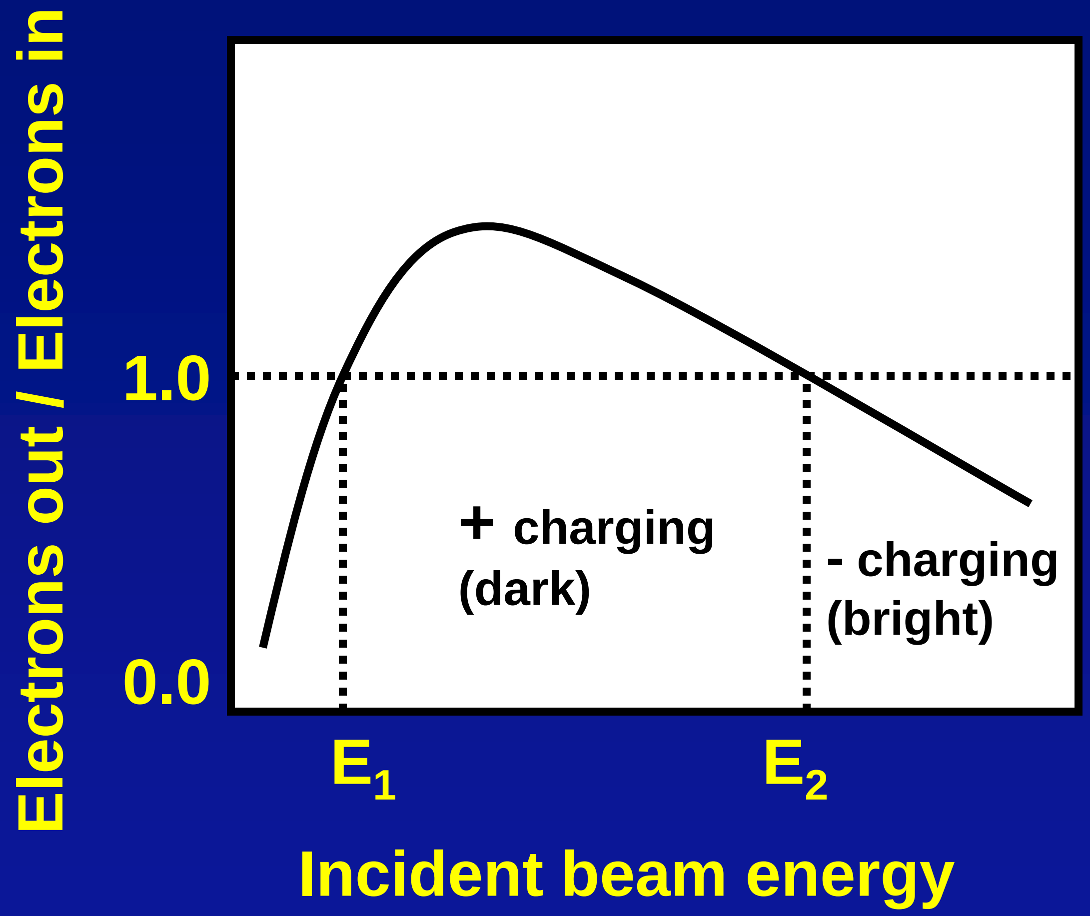


500 μm ——— **Mag = 35 x**

Low mag distorted image

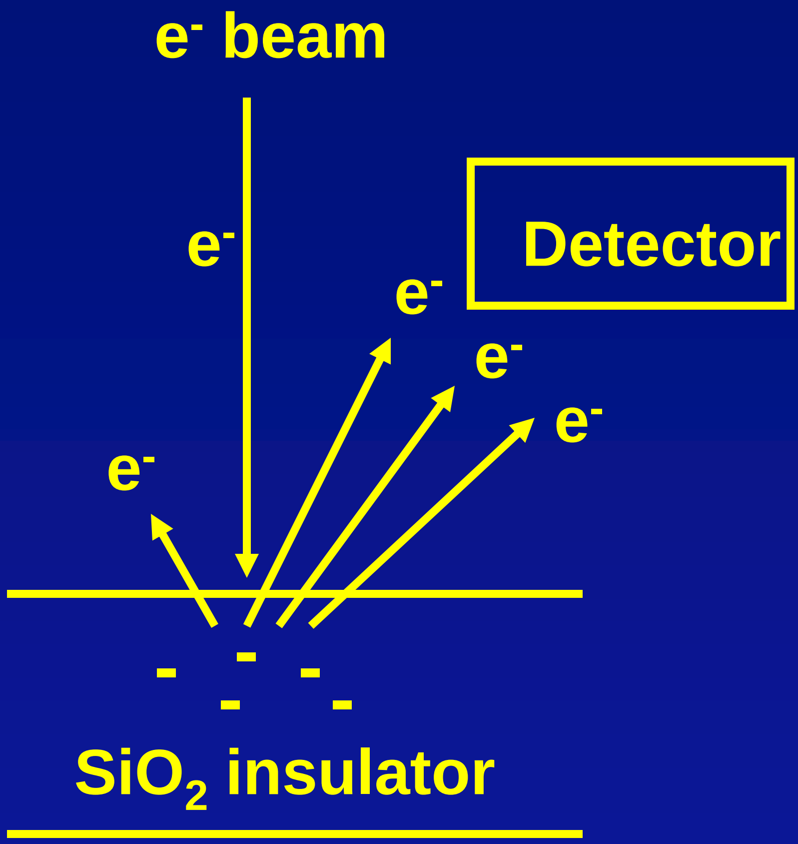
Electron beam charging

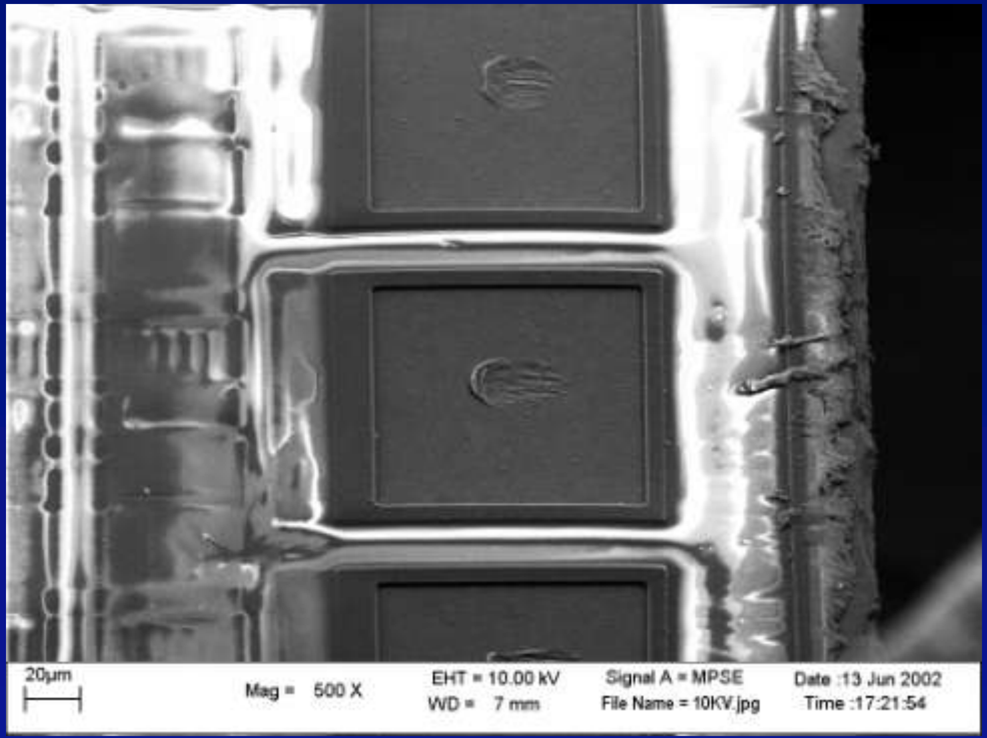




E_2 ~ 0.4 keV to 4.0 keV

Charging examples



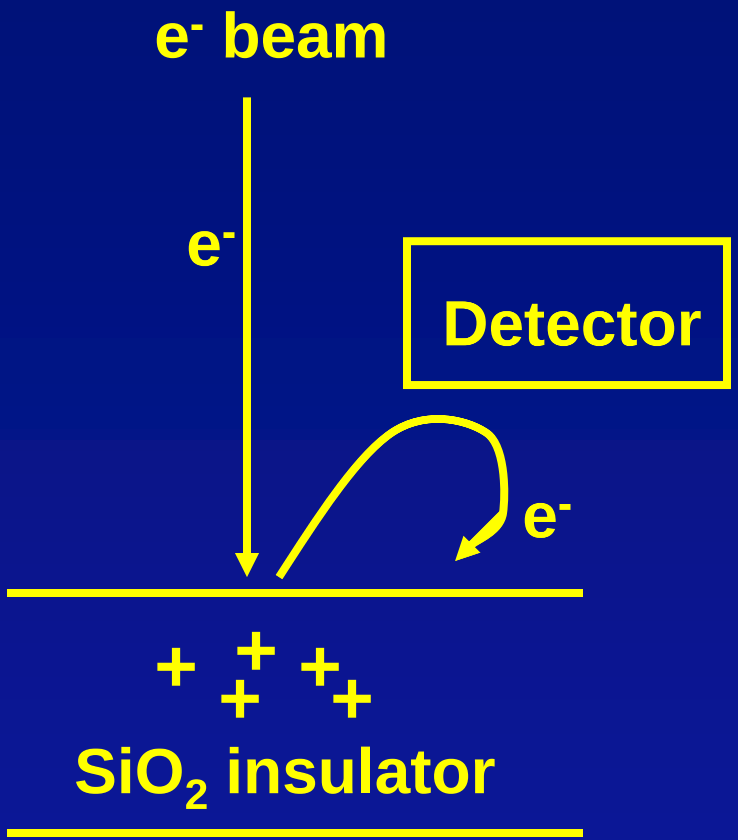


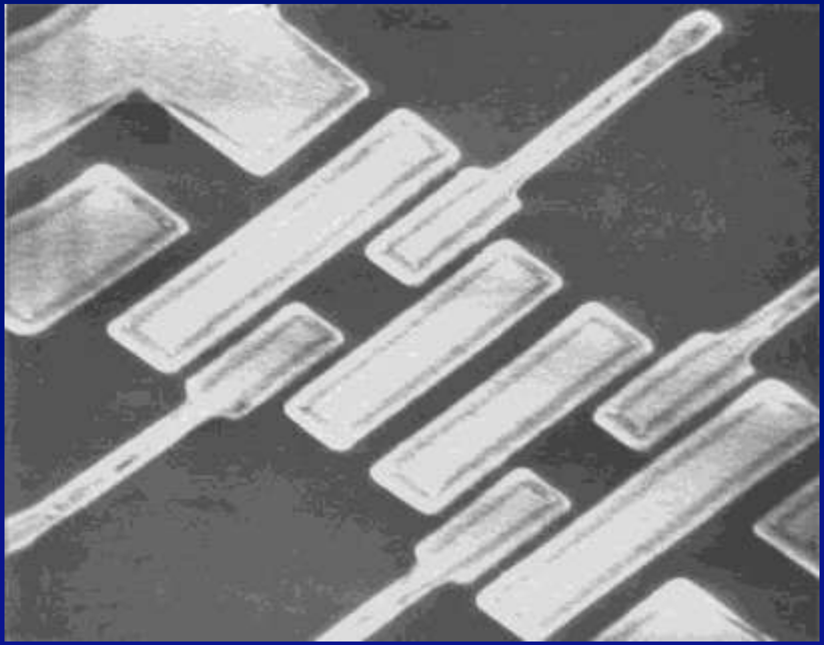
20 µm — Mag = 500x

Beam energy = 10 keV

Negative (bright) charging

Charging examples





10 μm

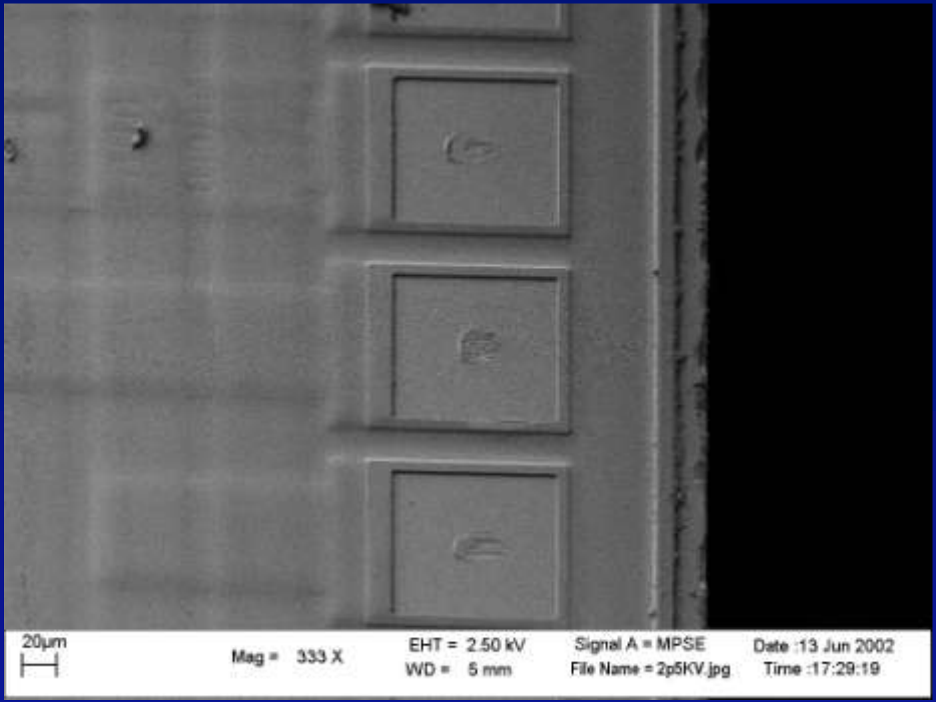
Mag = 2000x

Beam energy = 1.0 keV

Positive (dark) charging

Beam energies that reduce charging

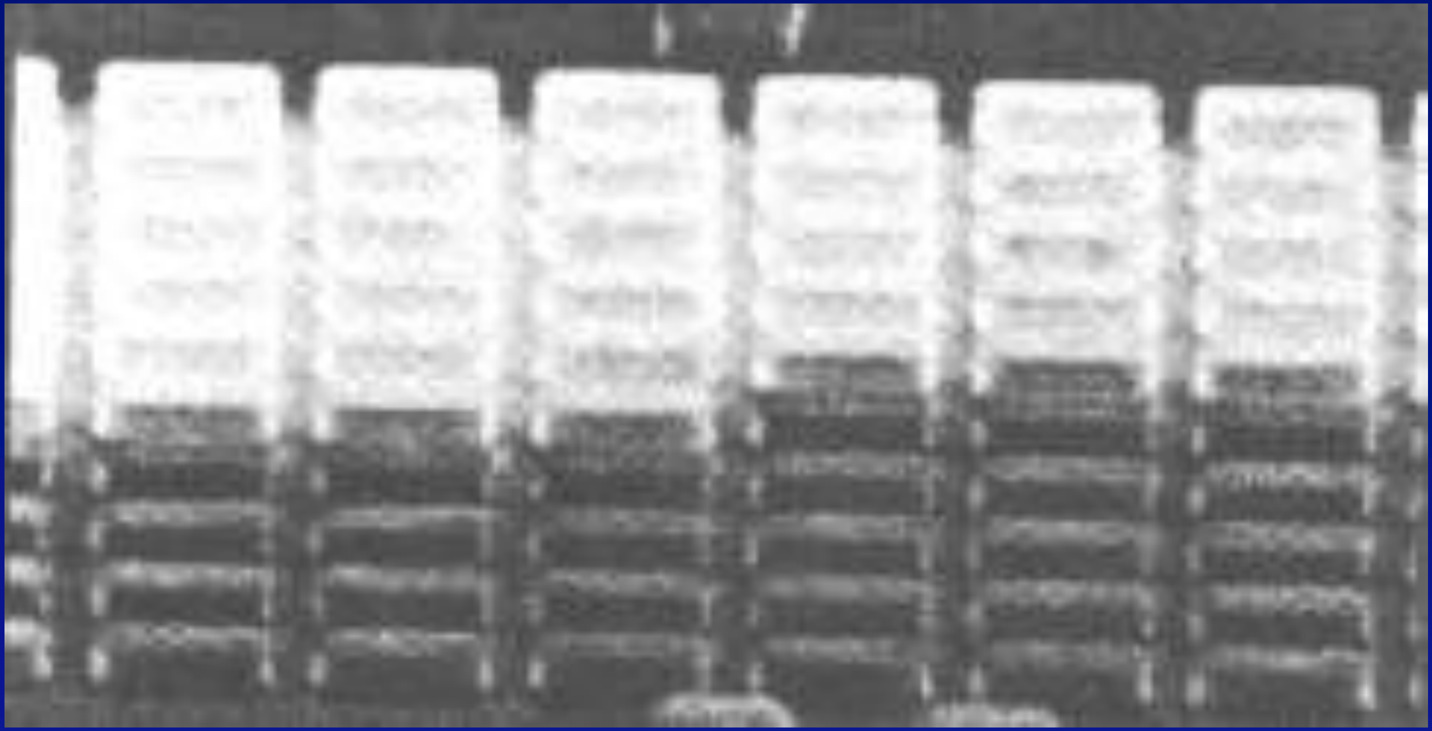
Material	E_2 (keV)
Polyimide	0.4
Photo Resist	0.55 – 0.70
PVC	1.65
Teflon	1.82
Glass Passivation	2.0
GaAs	2.6
Quartz	3.0
Alumina	4.2



20 µm – Mag = 333x

Beam energy = 2.5 keV

Passive Voltage Contrast Example



From S. Bothra et al., "A New Failure Mechanism by Corrosion of Tungsten in a Tungsten Plug Process", Proceedings of the IRPS, 1998, pp. 150-156.

Slide courtesy Ed Cole

What about beam damage?

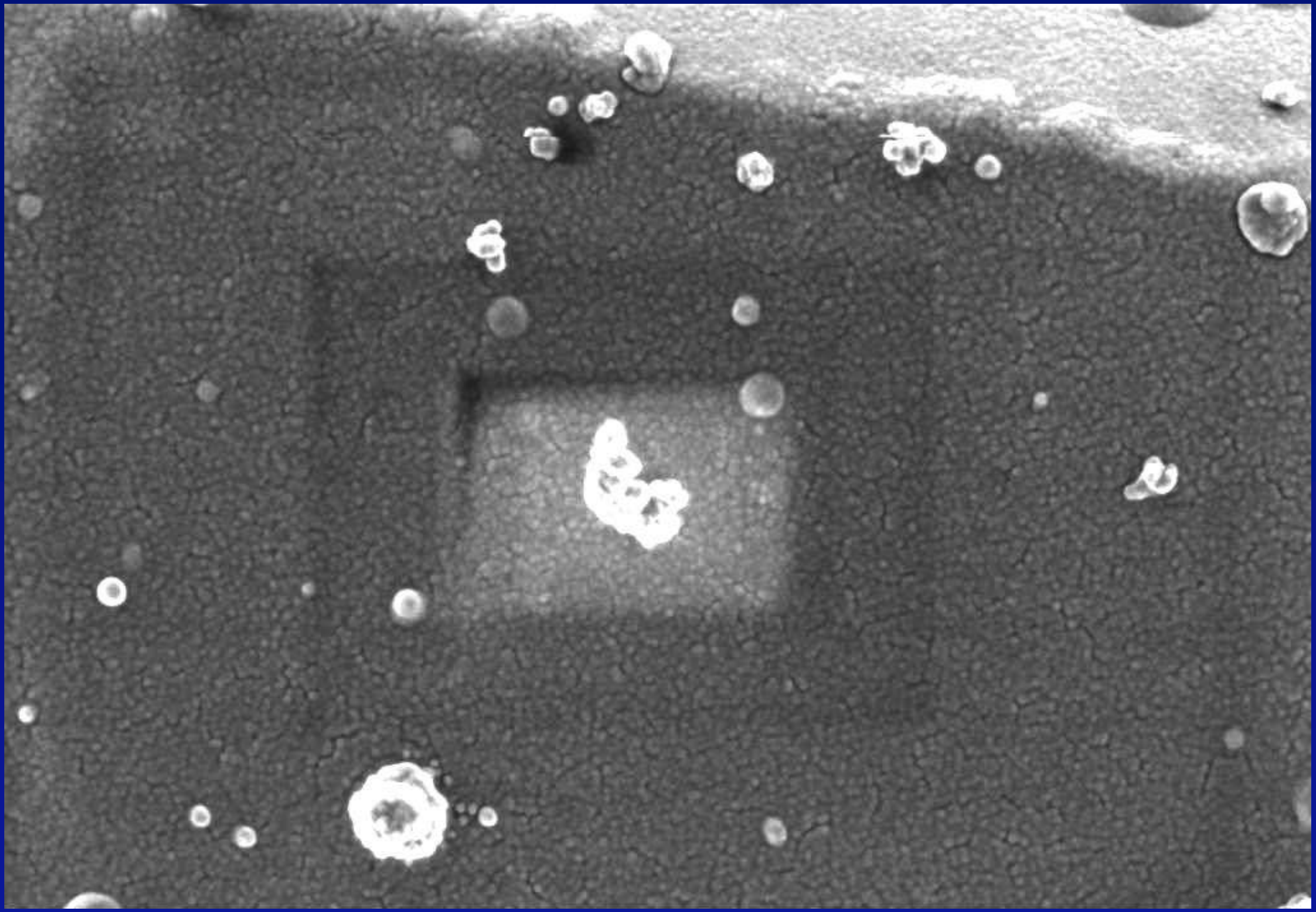
• "Raster burn" is often just sample charging which goes away when sample is vented to atmosphere.

• Large current in a small area can cause carbon deposition, especially if vacuum is poor.

• Large current on delicate samples (polymers) can melt or cause electrostatic discharge.

• If the electron beam penetrates to the gate, CMOS transistors may see threshold voltage shifts. This can generally be annealed out at 150 C for ~30 minutes.

“Raster Burn”

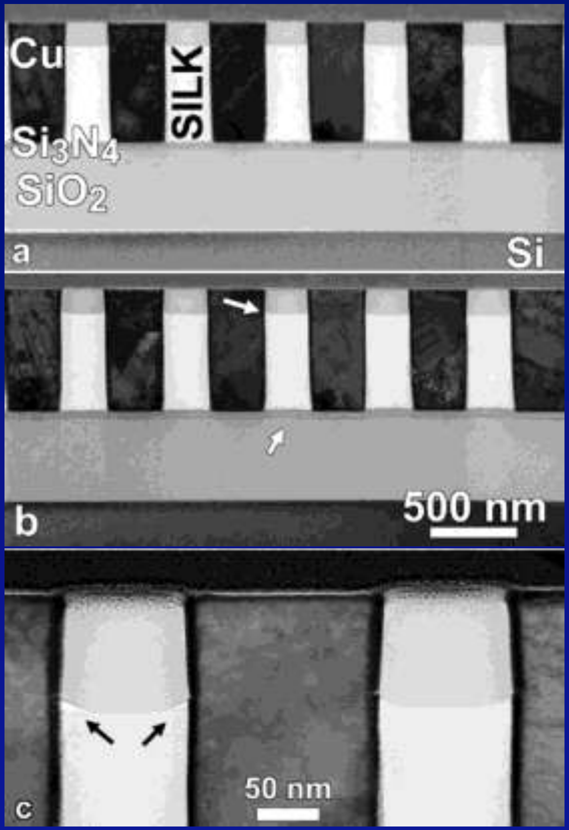


200 nm

Mag = 60,000x

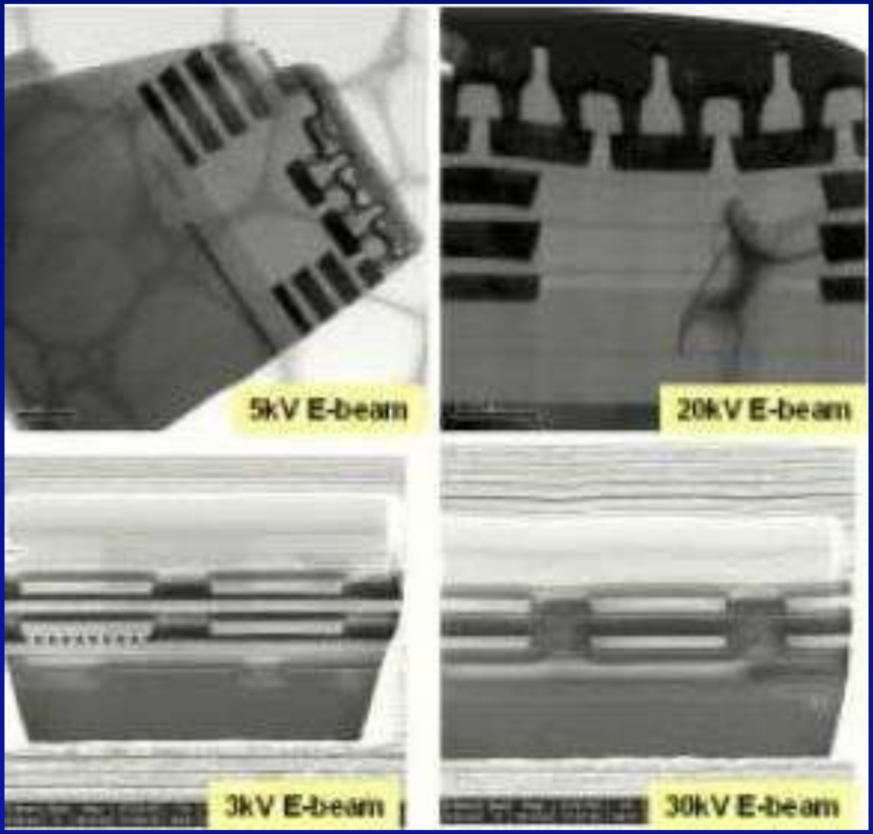
Low-K materials

Easily damaged by high energy electron beam



TEM

TEM



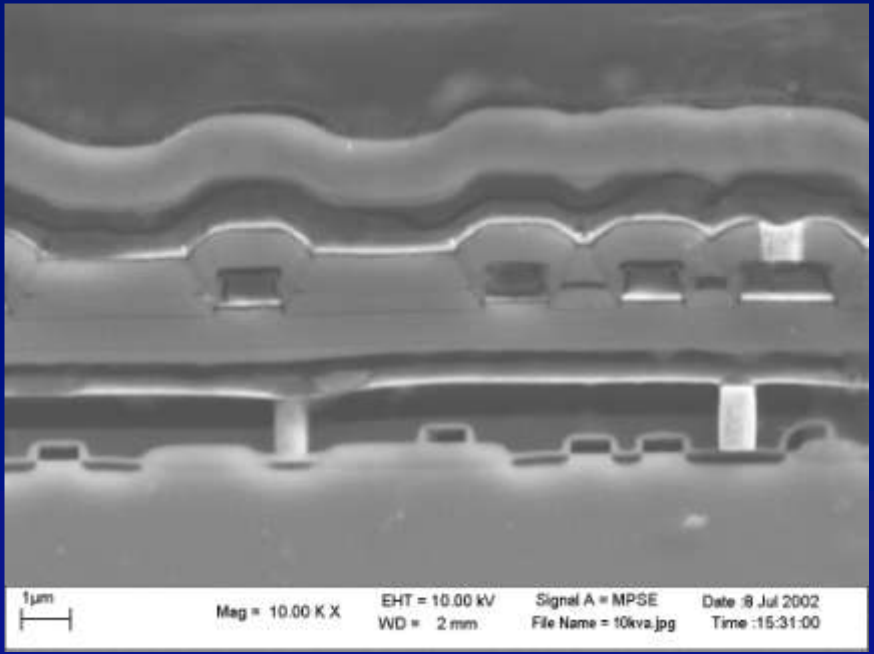
SEM

H. Bender, R.A. Donaton, ISTFA 2001

L. Li-Lung, ISTFA 2005

Sample Prep – Cross Sections

- Mechanical polish or FIB
- Automated fracture tools
- Staining and delineation



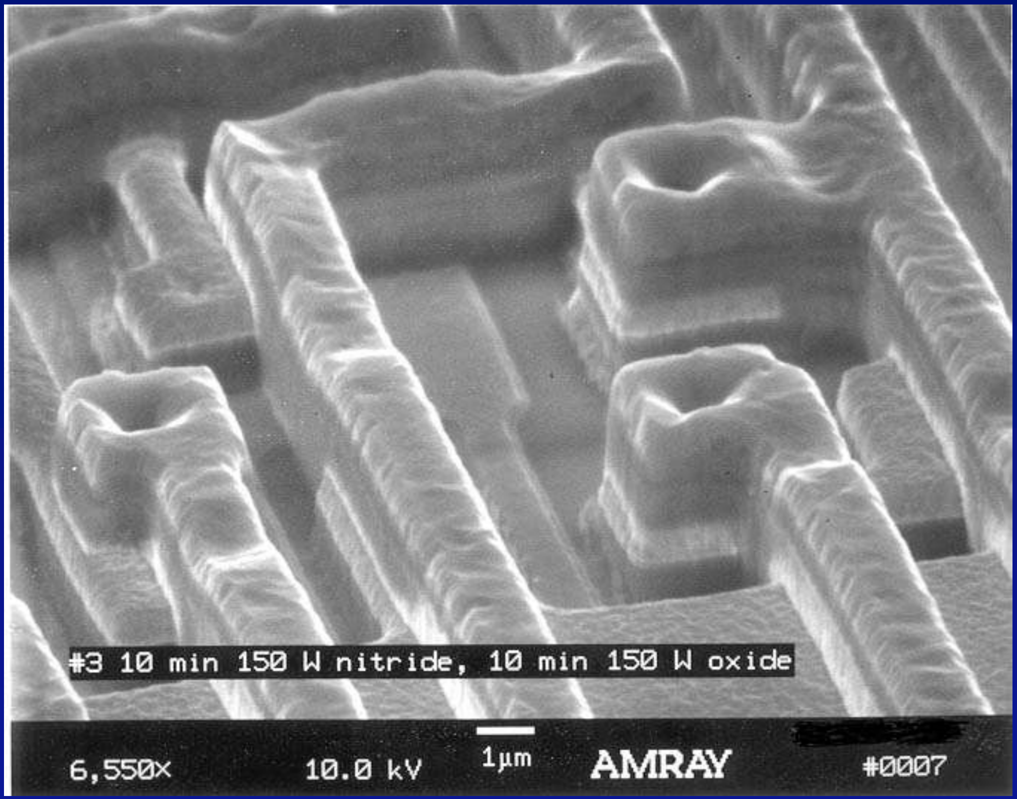
1 µm ─ Mag = 10,000x

Typical Junction stain:
10:3:1 Acetic:Nitric:HF with bright light
Can add a few drops of copper sulfate solution

Typical oxide delineation: buffered oxide etch

Sample Prep – RIE Deprocessing

- Reactive ion etching
- Selective to metal or dielectric
- Can be directional or isotropic
- May produce “grass” artifacts

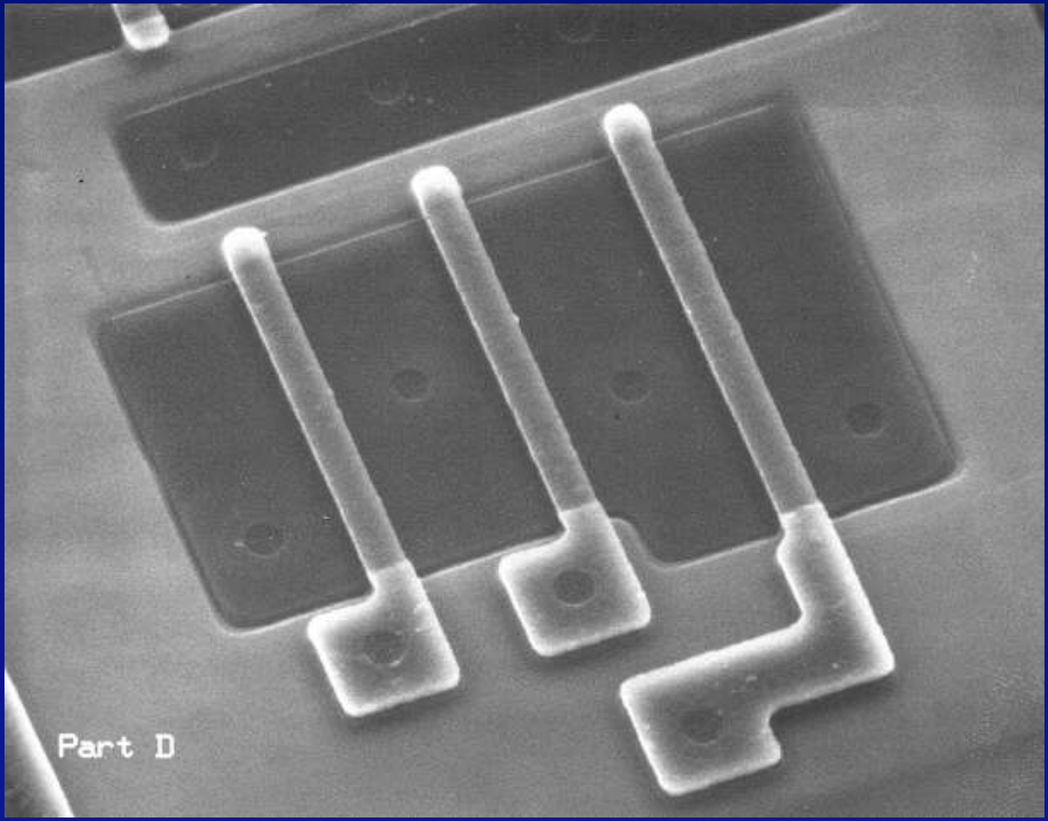


1 μm —   Mag = 6,550x

SEM of reactive ion etched circuit

Sample Prep – Wet Deprocessing

- Wet chemical etching
- Very selective to materials
- Usually isotropic and will undercut layers
- Can be difficult to control



10 μm

Mag = 4,000x

SEM of circuit after HF chemical strip

Getting a good image

- Mounting the sample
- Selecting beam voltage
- Selecting working distance
- Column alignment and de-gaussing
- Reduce or eliminate charging
- Focus and Stigmate the image
- Adjust the contrast and brightness

Sample mounting

Wish list: fast and easy, mechanically rigid, conductive, doesn’t damage sample

- **Spring clips & screw mounts – fast & easy, rigid, but may damage sample**

- **Carbon or silver paint – rigid, safe, but slow**

- **Metal tape, double sticky carbon dots – fast & easy, but not rigid**

Selecting beam voltage

Maximum brightness ~ beam voltage

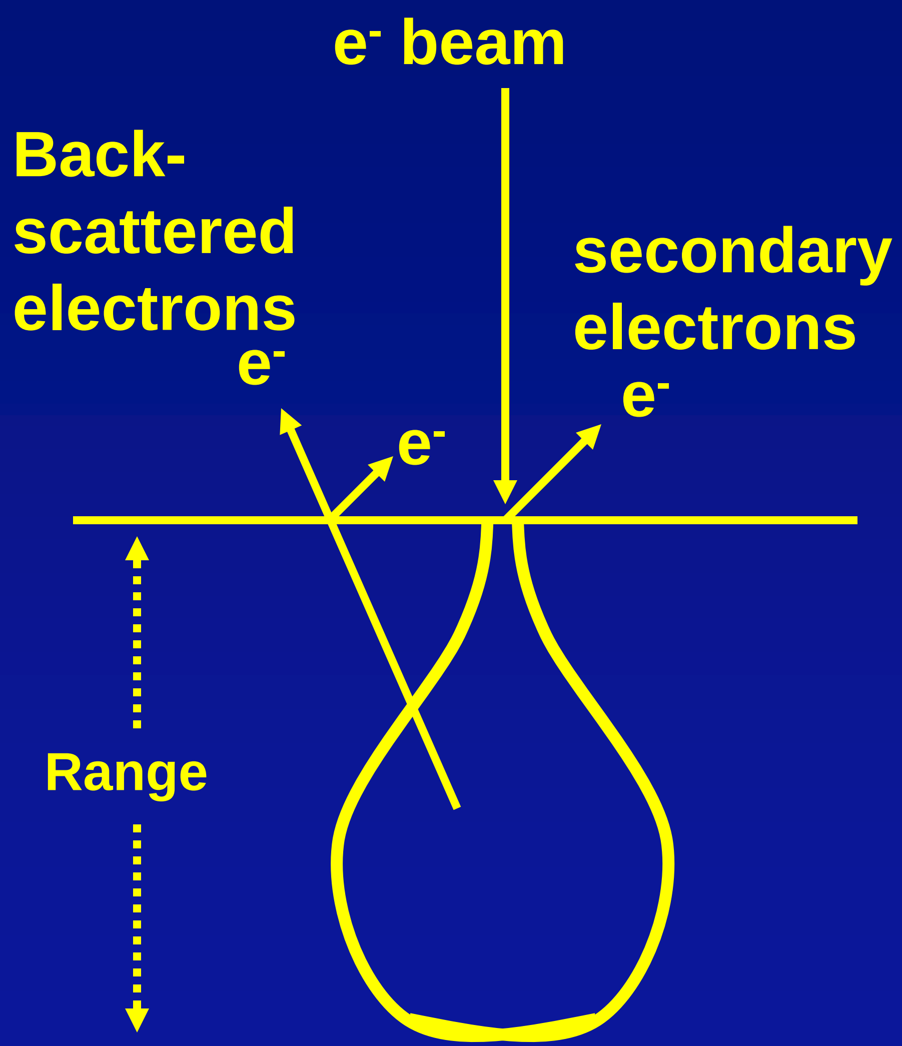
- High voltage produces higher brightness and smaller spot size for higher resolution

- But lower beam voltage is more sensitive to surface detail and can reduce charging

- Use the lowest beam voltage you can

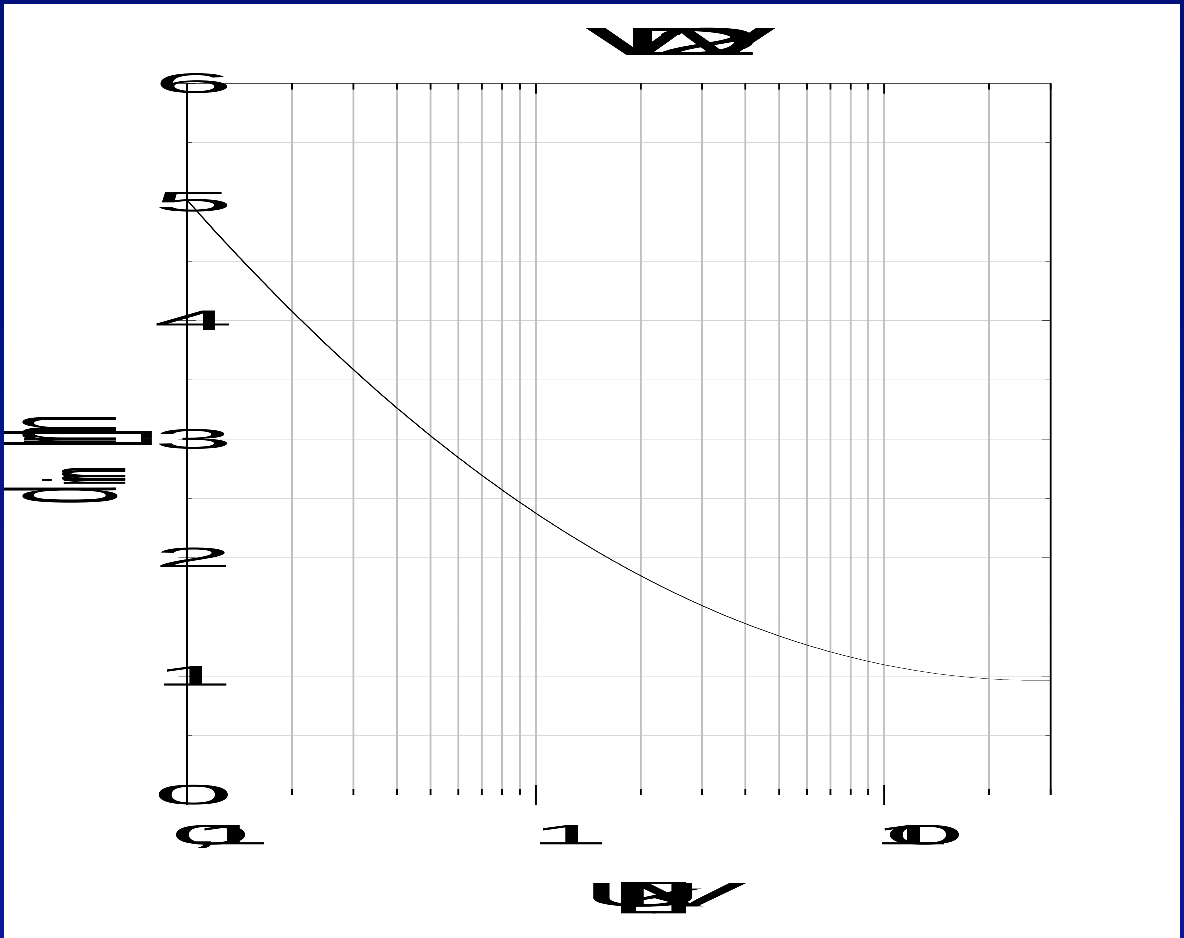
Electron beam energy vs. range & spot size

Beam energy (keV)	Spot size (nm)	Range in Al (μm)
1	2.4	0.028
3.5	1.5	0.22
5	1.3	0.41
10	1.1	1.32
20	1.0	4.19
30	1.0	8.24



Range calculated from the Kanaya-Okayama formula

LEO 1550 FE "Gemini" Column Specs

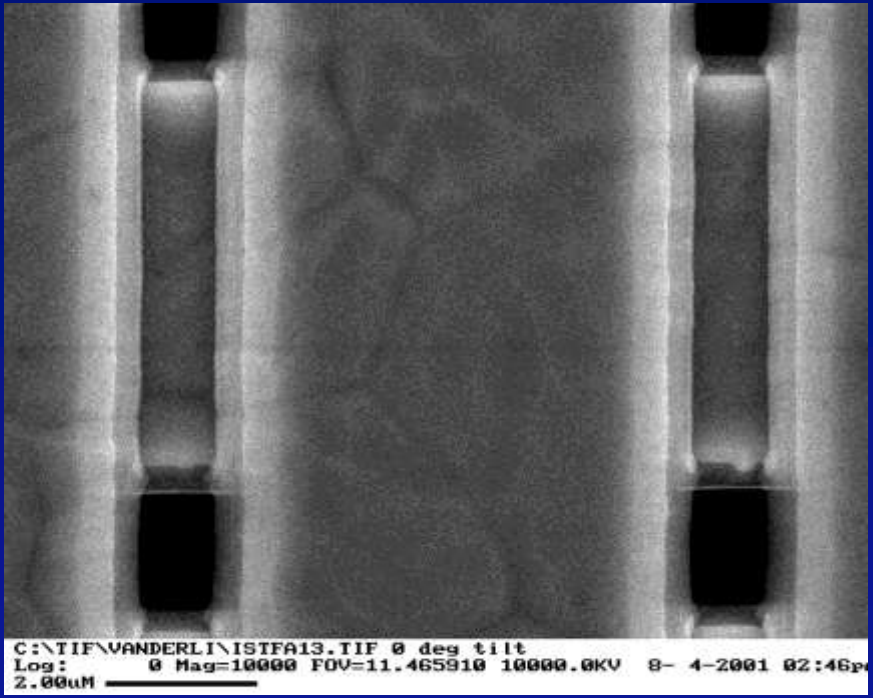


d = 1.0 nm @ 20 kV

d = 2.3 nm @ 1 kV

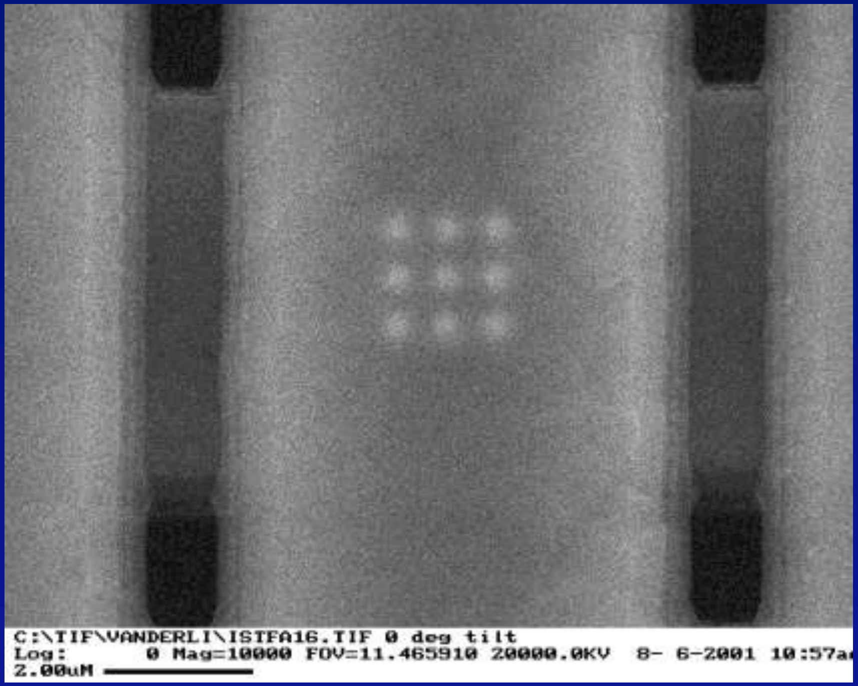
Resolution vs. beam voltage for LEO 1550 FE

Beam Voltage vs. image detail



2 μm ——— Mag = 10,000 x

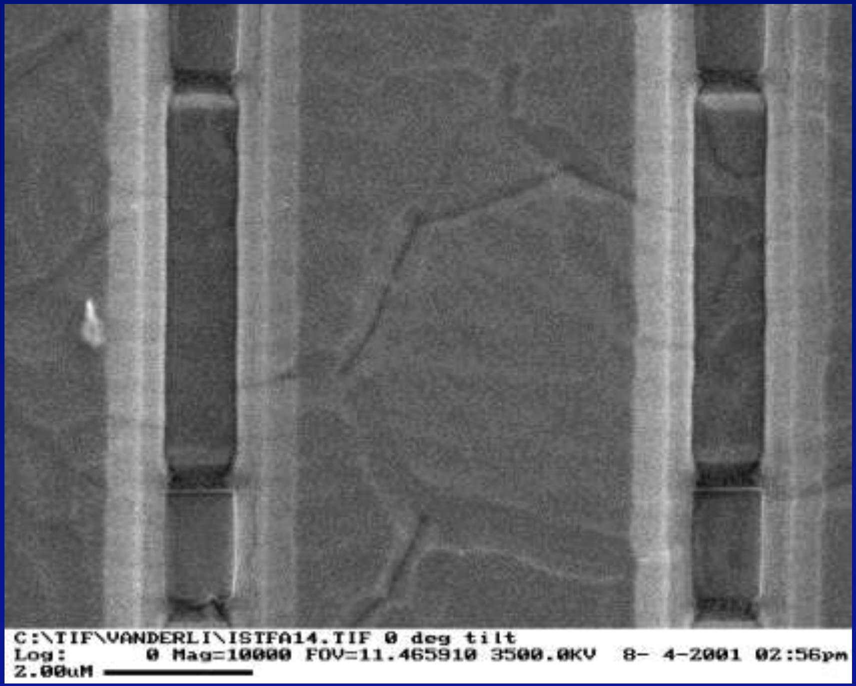
10 kV beam voltage



2 μm ——— Mag = 10,000 x

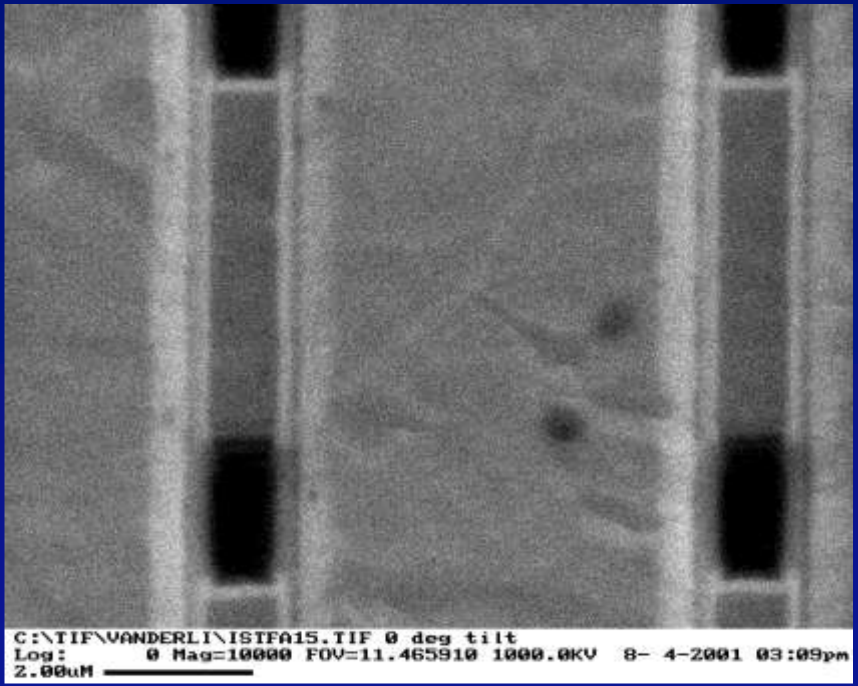
20 kV beam voltage

Voltage vs. image detail



2 μm ——— Mag = 10,000 x

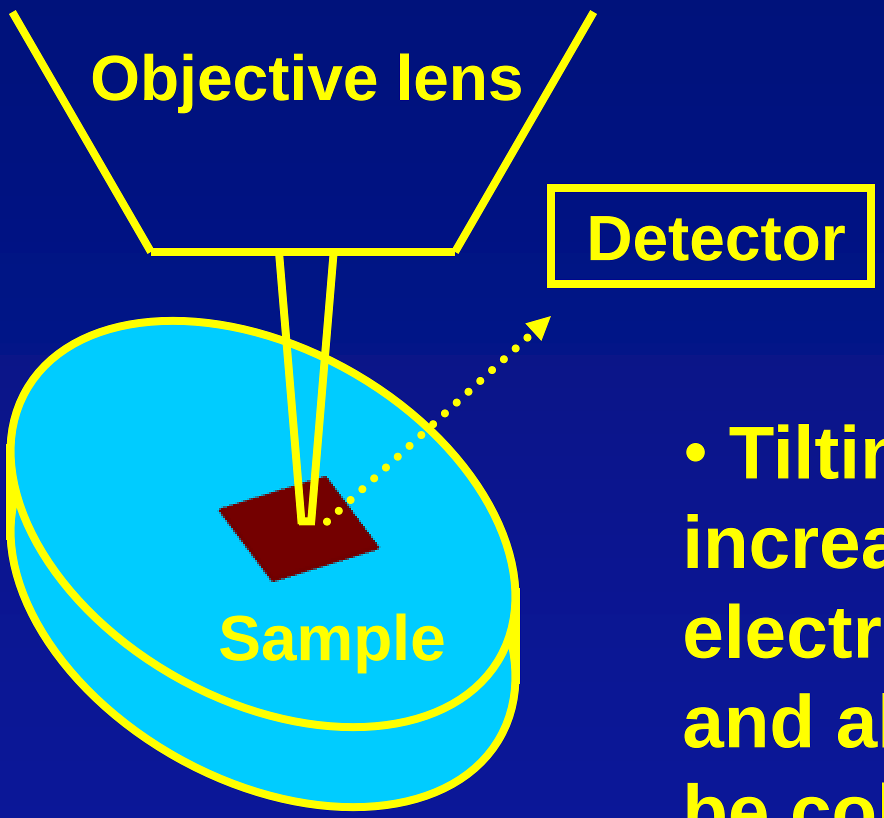
3.5 kV beam voltage



2 μm ——— Mag = 10,000 x

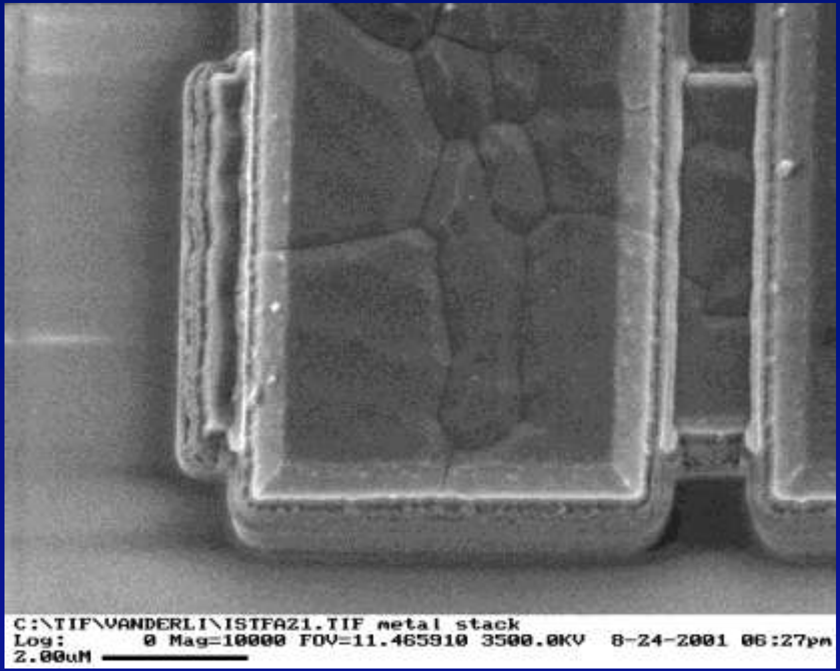
1 kV beam voltage

Sample Tilt



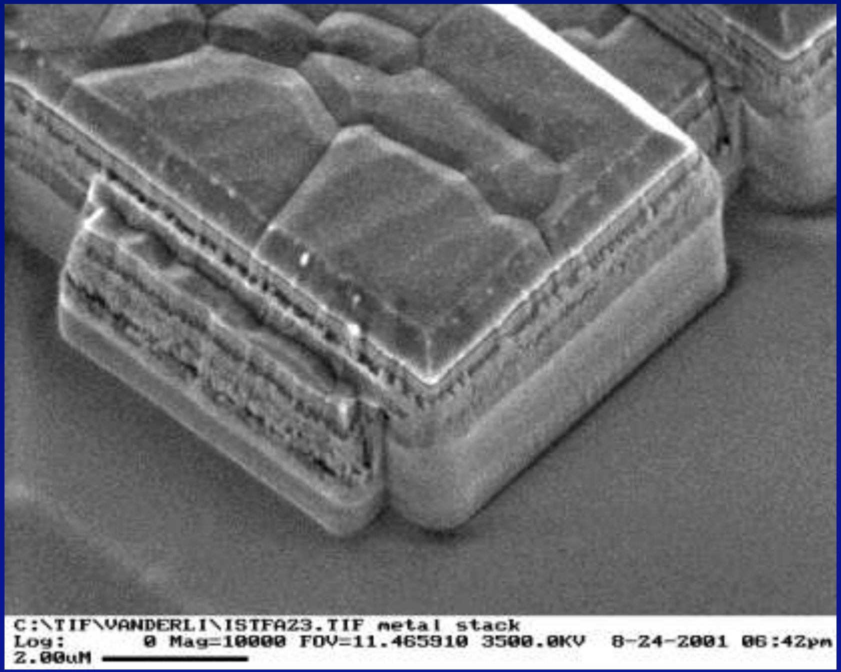
• Tilting toward the detector increases the secondary electron emission coefficient and allows more electrons to be collected

Composing an image



2 μm ——— Mag = 10,000 x

No tilt



2 μm ——— Mag = 10,000 x

30 degrees tilt
45 degrees rotation

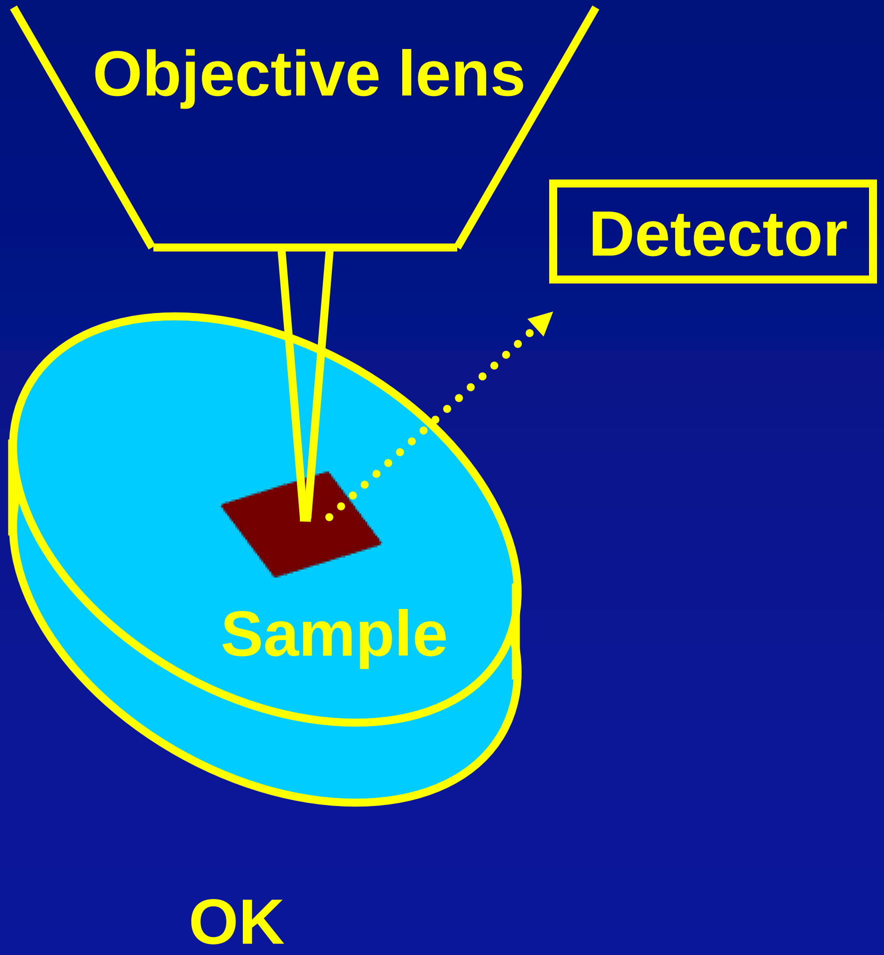
Short working distance

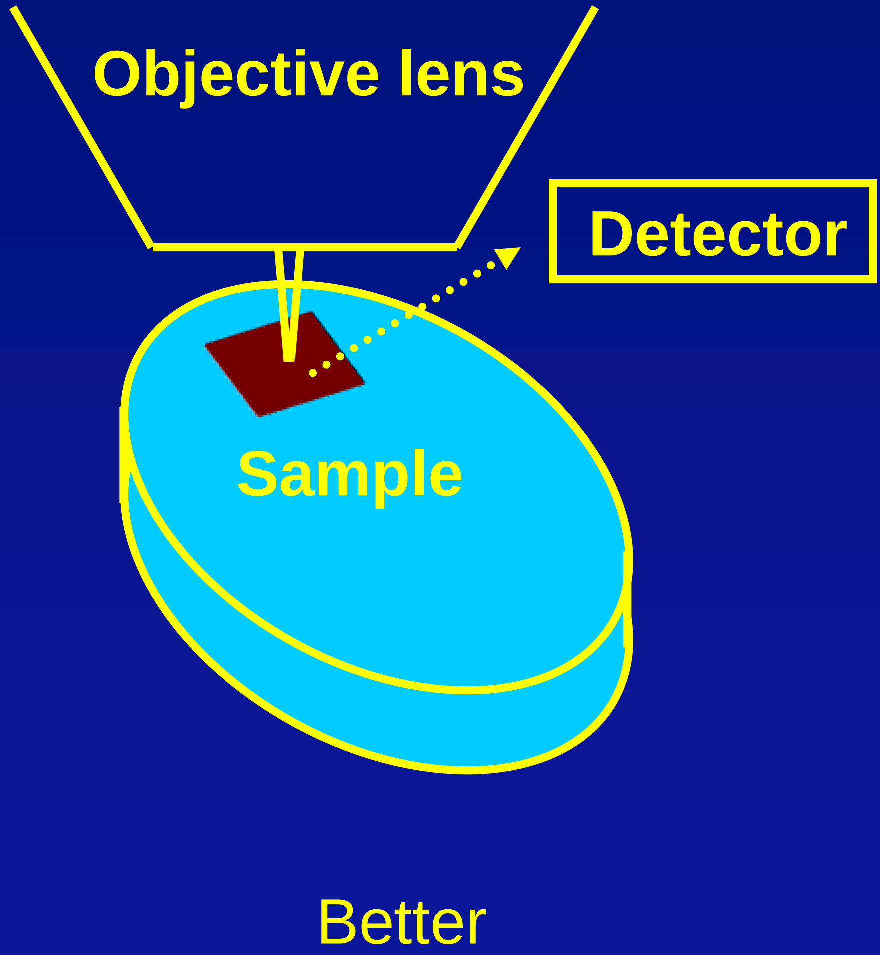
- Short working distance decreases the beam spot size and allows for sharper high magnification images

- For many SEMs, a working distance of 2 mm to 10 mm is optimum for high resolution

- Long working distance improves depth of field and reduces pincushion or barrel distortion

Achieving short working distance





Reducing electron beam charging

- Good electrical contact between the sample and the holder

- Use in-lens detector or variable pressure

- Increase tilt angle

- Reduce beam voltage

- Adjust beam current, raster area, raster rate

- Sputter coat sample with ~ 2 to 10 nm
  of Au/Pd, Cr, Pt, Ir, or C

Sputter coating samples

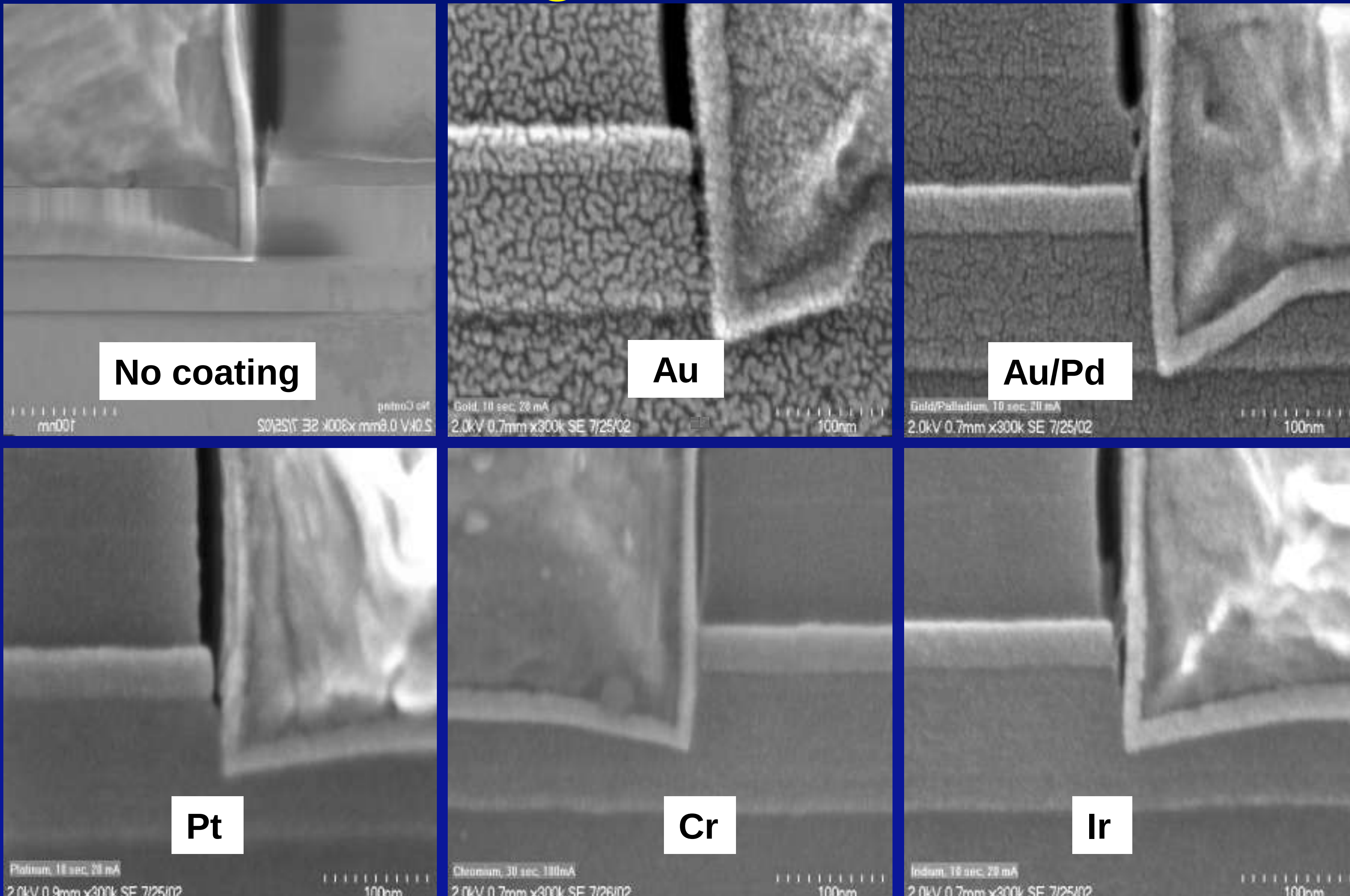
Pro:

- **Sputter coating completely eliminates charging**
- **It increases electron emission from the surface**
- **It decreases the range of secondary electrons, thus increasing the surface sensitivity of the image**

Con:

- **You are imaging the coating, not the sample**
- **You may see artifacts from the coating grains**
- **You must complete all sample preparation such as plasma etching or chemical staining prior to sputter coating**
- **It may be more difficult to use energy dispersive x-ray analysis if you sputter coated with metal**

Coatings at 2kV; 300kX



From R. Holdford and A. Vance, Scanning 2006

Sputter coating materials

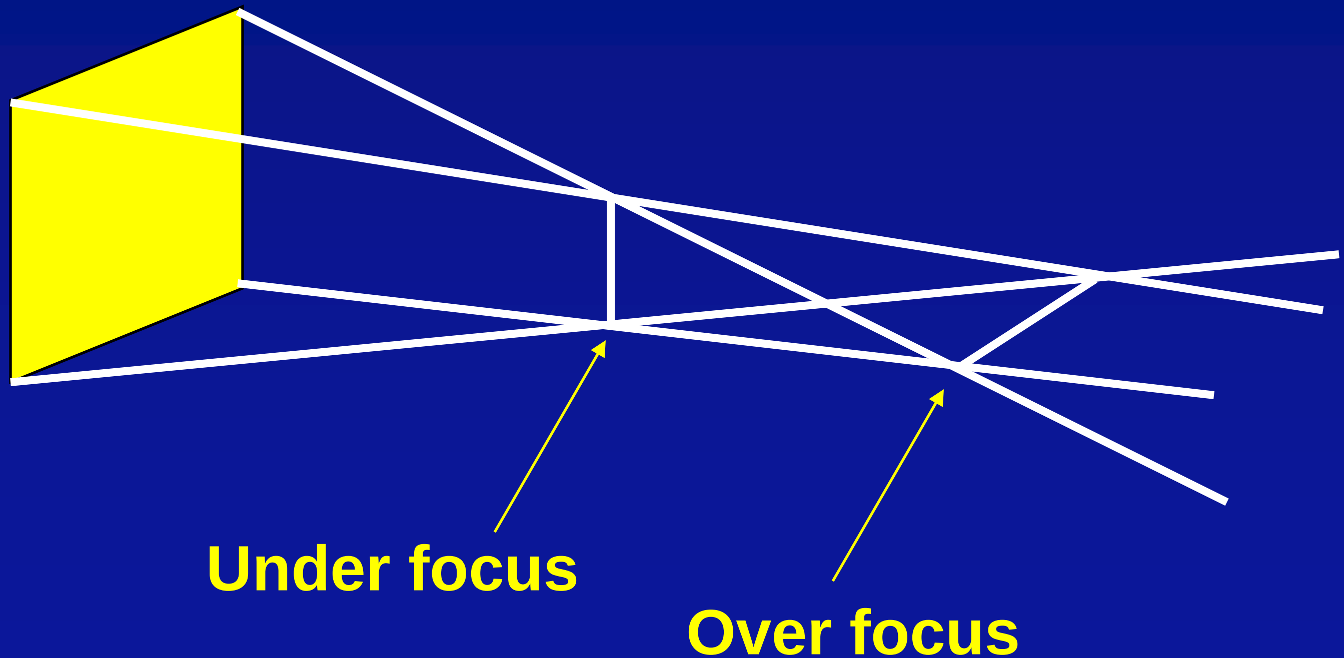
- Au – very course grain size
- Au/Pd – course grain size
- Cr – fine grain size (but oxidizes in air)
- Ir – fine grain size (but requires high RF power, not compatible with some sputter coaters)
- Pt – fine grain size

[Au, Au/Pd, Pt coatings can be removed with aqua regia]

- Carbon – not as good for imaging (poor electron emissivity and range) but is x-ray transparent and can be removed with an oxygen plasma.
- Carbon sputters very slowly in a Ga ion beam and is a good definition layer between FIB deposited metals

Astigmatism

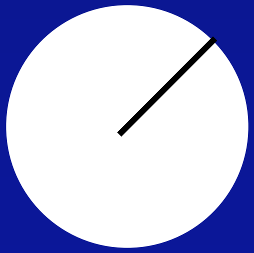
- Spherical asymmetry of a lens
- Corrected by additional lens coils
- Same procedure for SEM and FIB



Stigmation

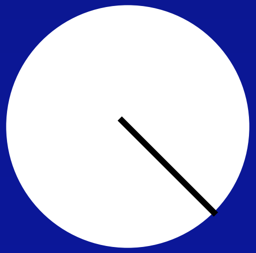
2 µm ——— Mag = 10,000 x

2 µm ——— Mag = 10,000 x



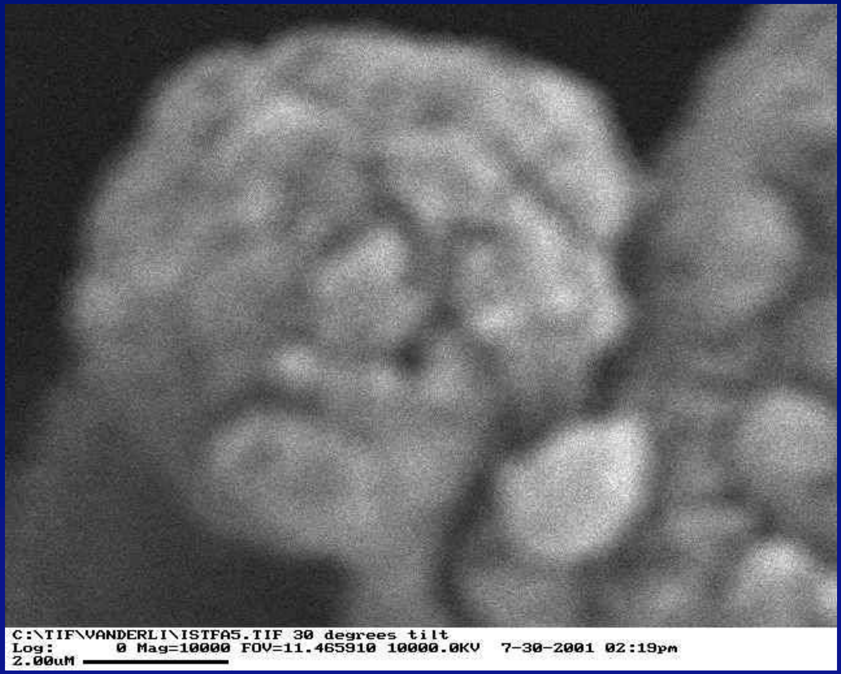
Under focus

Objective lens
(Focus knob)

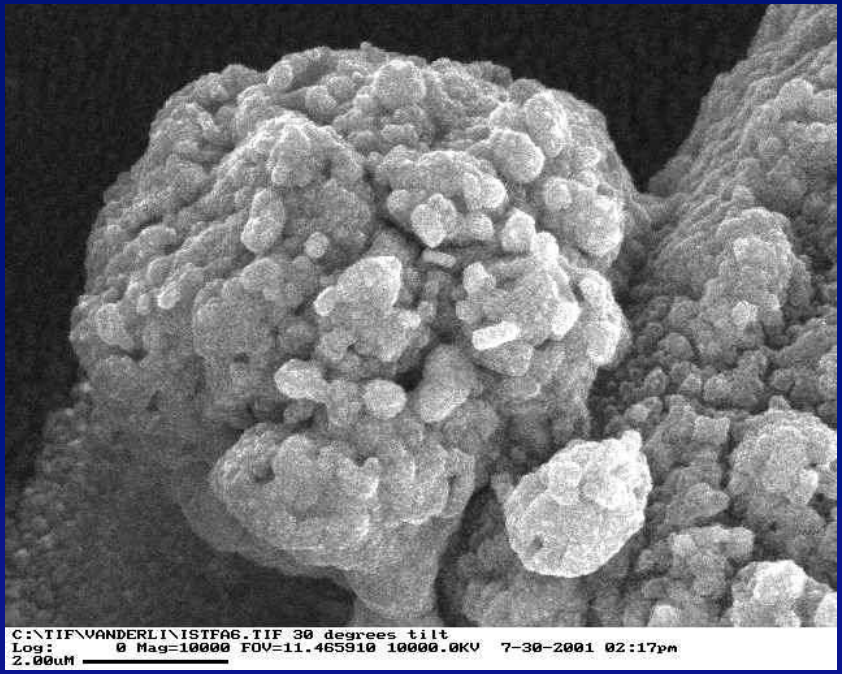


Over focus

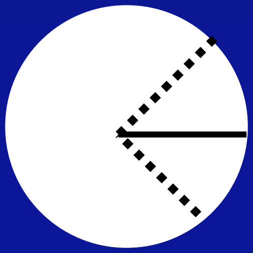
Correct focus



2 µm —— Mag = 10,000 x



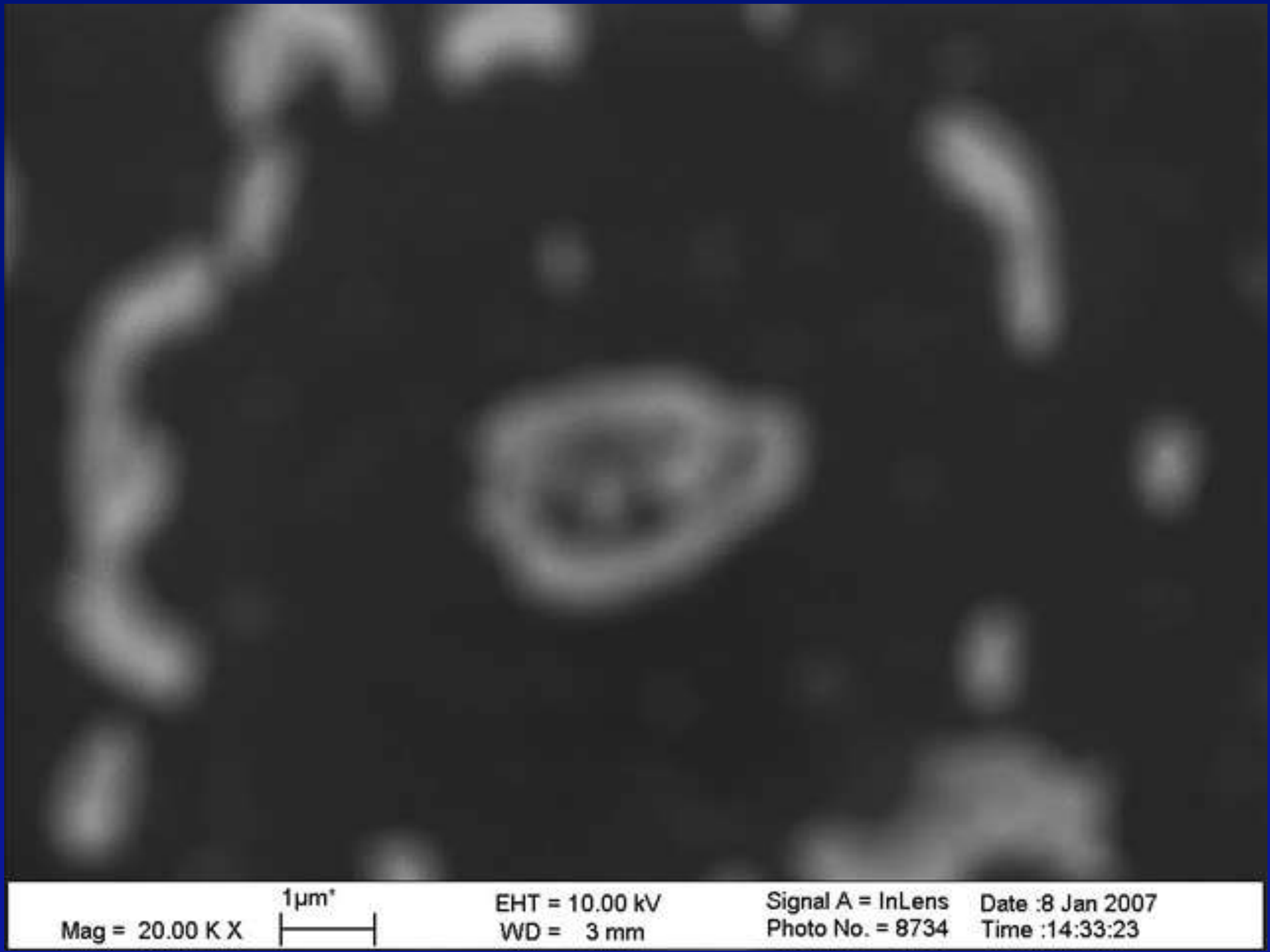
2 µm —— Mag = 10,000 x



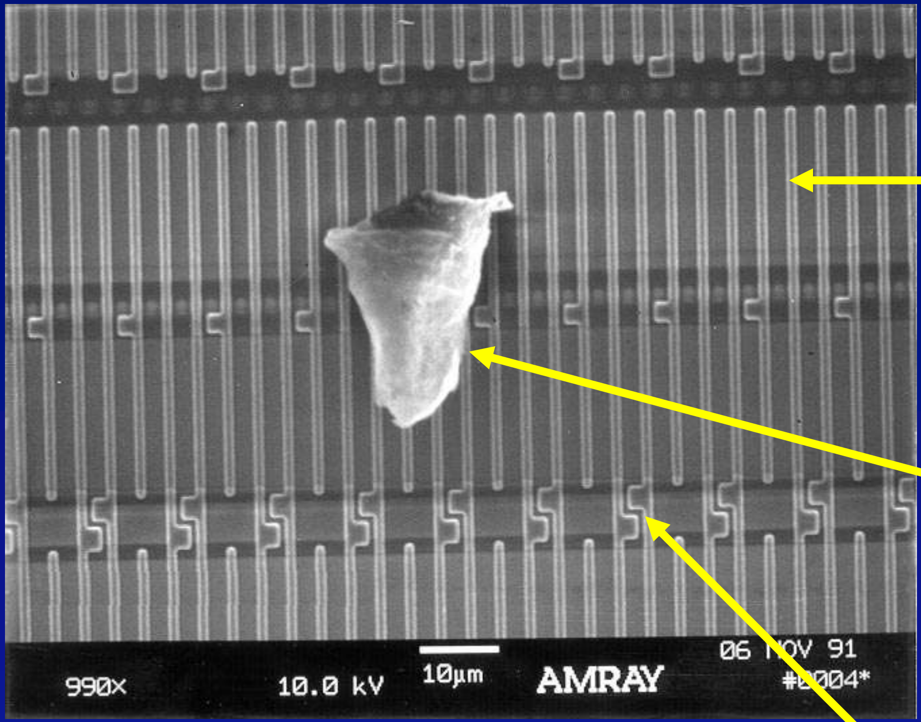
Correct focus

Correct focus with stigmation corrections

Focus/Stig movie



Picking a focus object



Avoid lines in only one direction

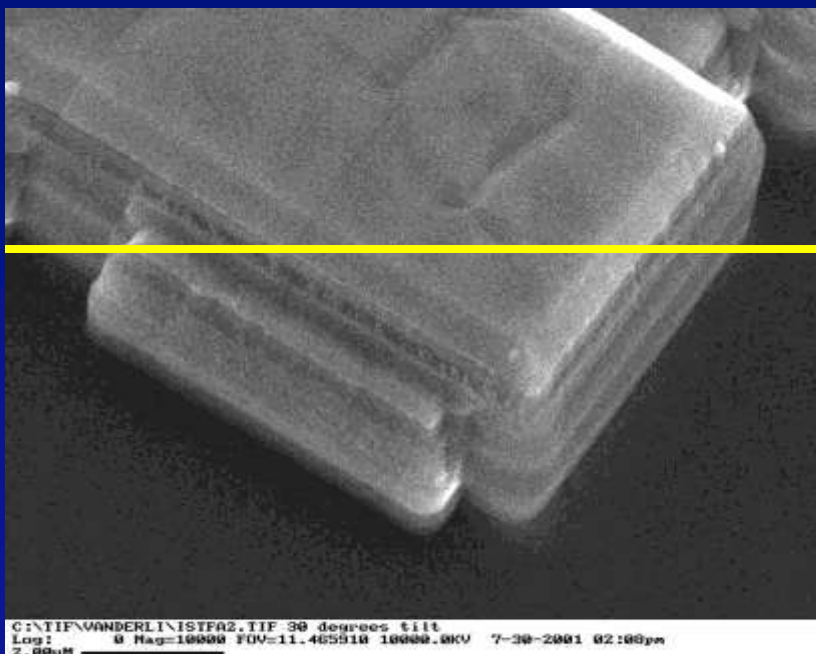
Dust particle –
OK if not charging up

Orthogonal lines –
also OK

10 µm —

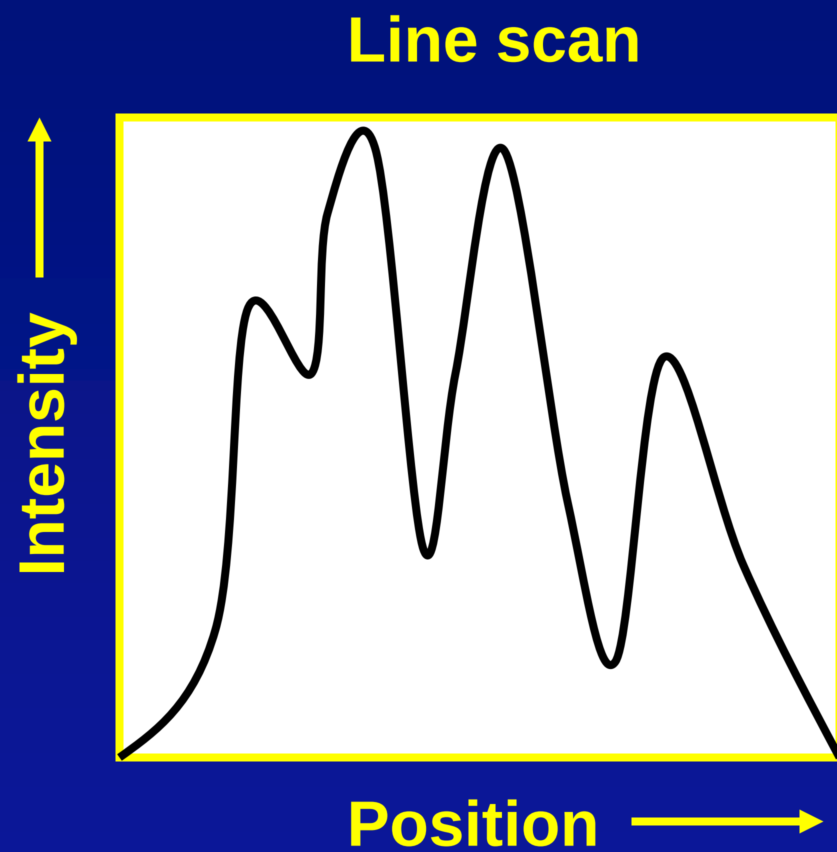
Mag = 990 x

Brightness and contrast

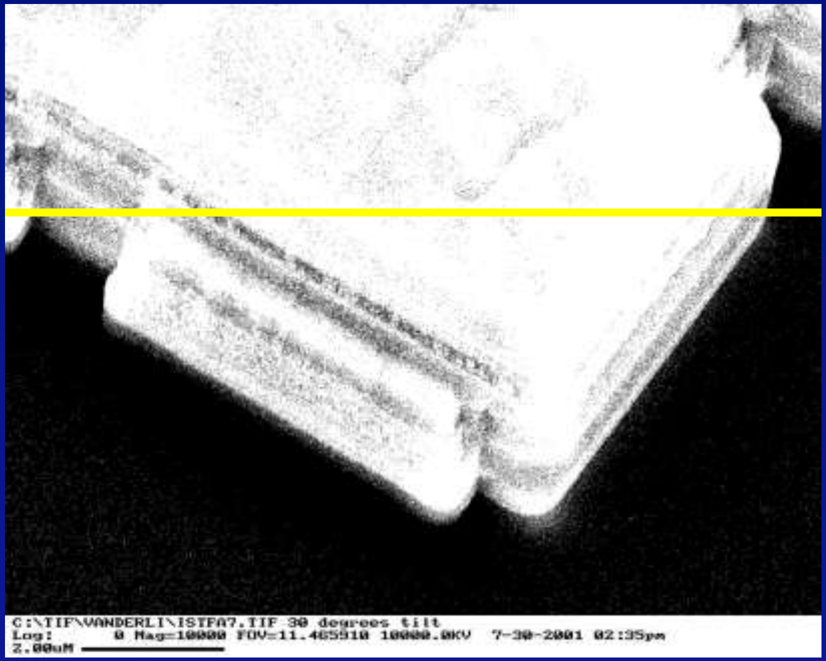


2 µm

Mag = 10,000 x



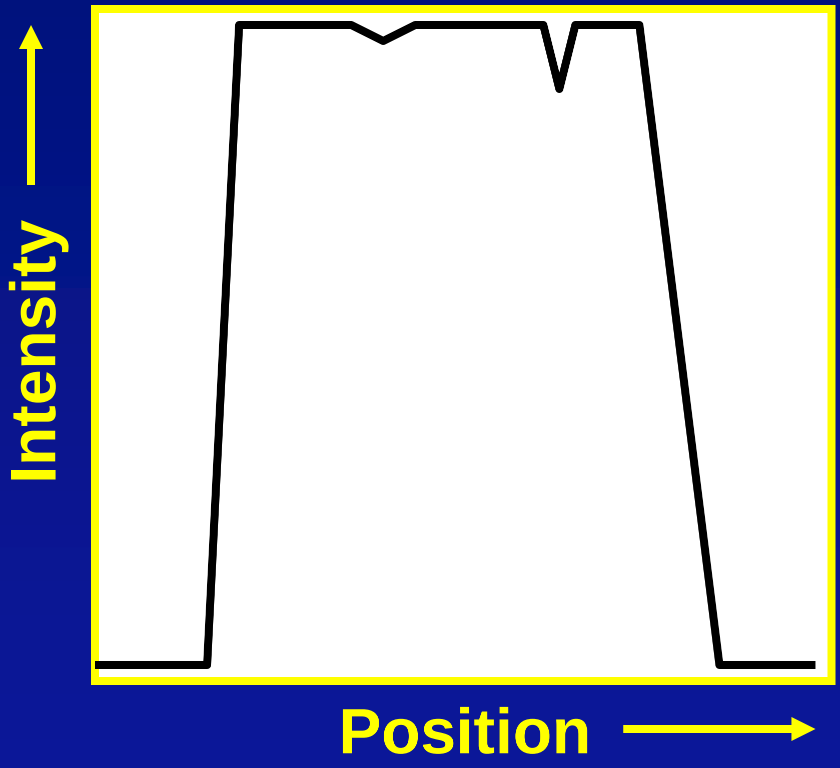
Too much contrast



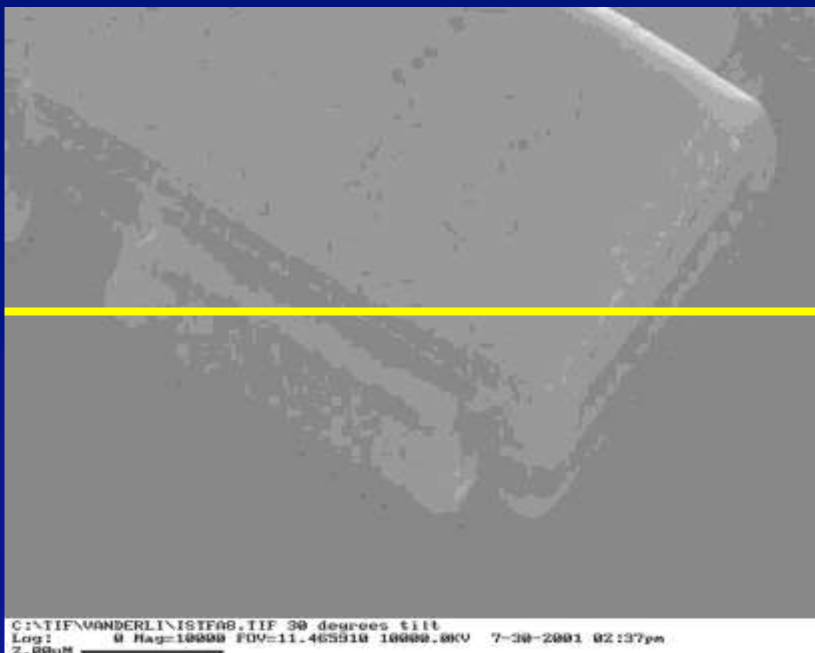
2 μm

Mag = 10,000 x

Line scan



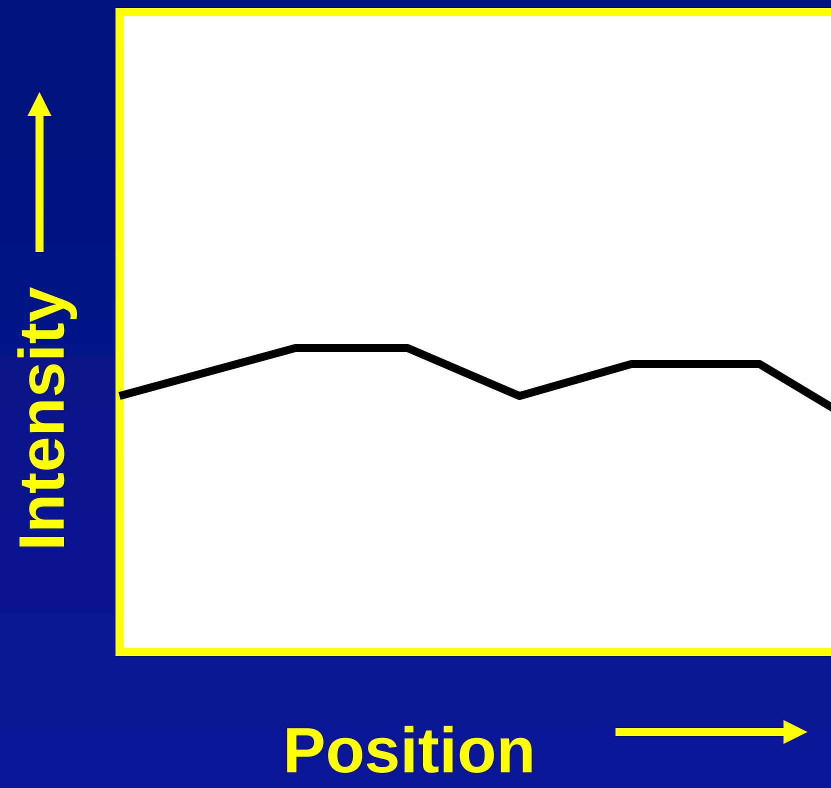
Not enough contrast



2 µm

Mag = 10,000 x

Line scan



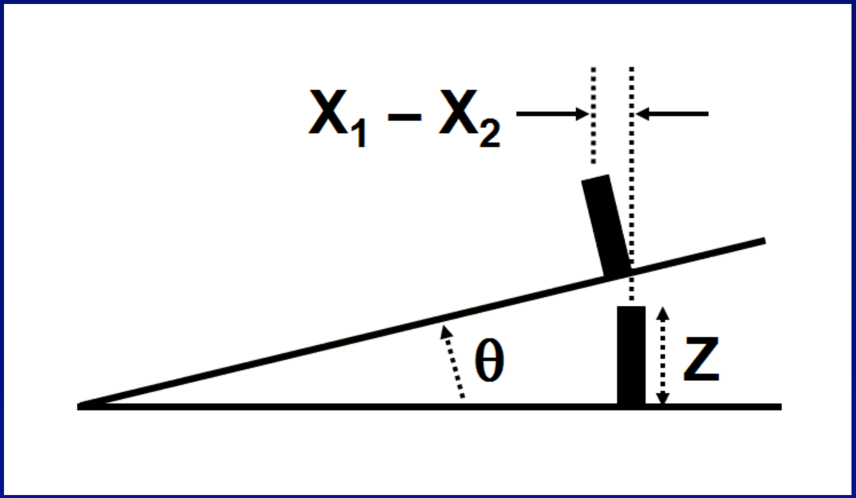
Stereo Imaging in the SEM

Red/blue anaglyph

Stereoscope for SEM images

Modern methods of displaying stereo images:
- **difficult to display to large audiences**
- **difficult to archive**
- **vertical height measurements are tedious**

Vertical Height Measurements



$$Z = (X_1 - X_2) / 2 \sin(\theta/2) \qquad \text{Eqn. 1}$$

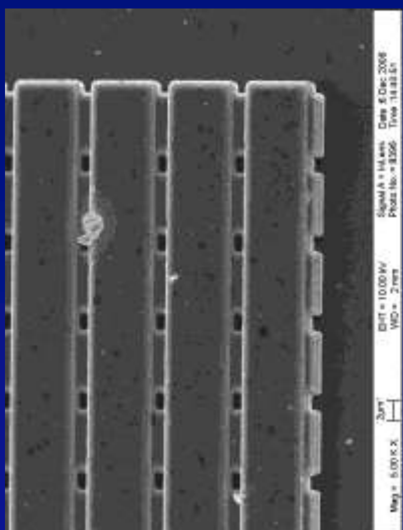
Where:

X_1 = distance in microns along the x-axis from the eucentric point to the feature in the first photo

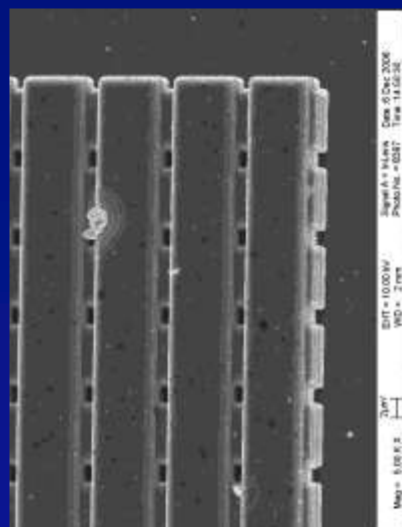
X_2 = distance in microns along the x-axis from the eucentric point to the feature in the second photo

θ = tilt change between photos

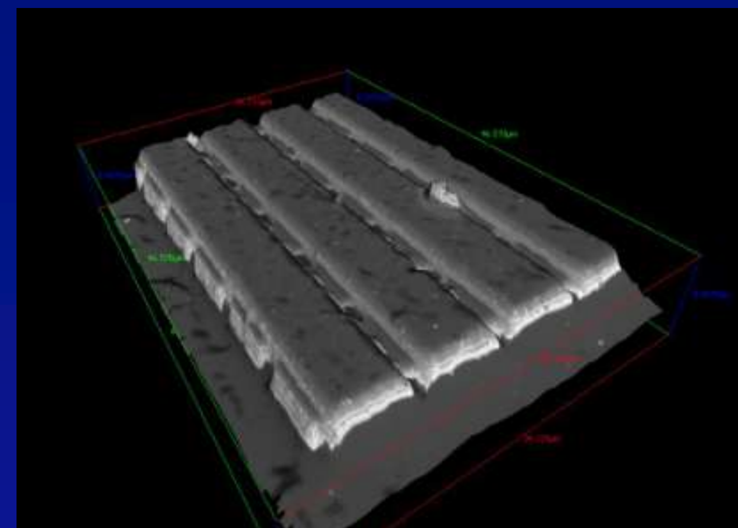
A new approach: Digital Elevation Models (DEM)



0^{o} tilt



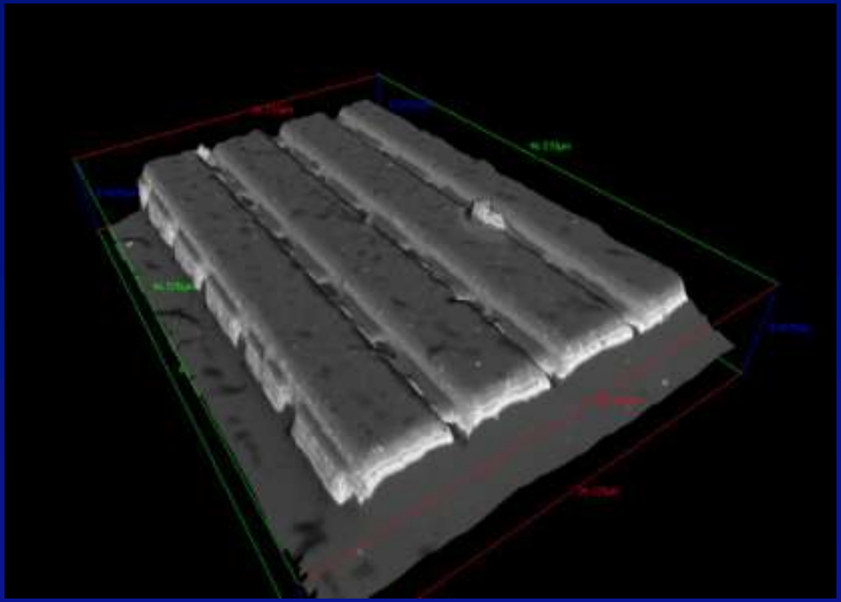
5^{o} tilt

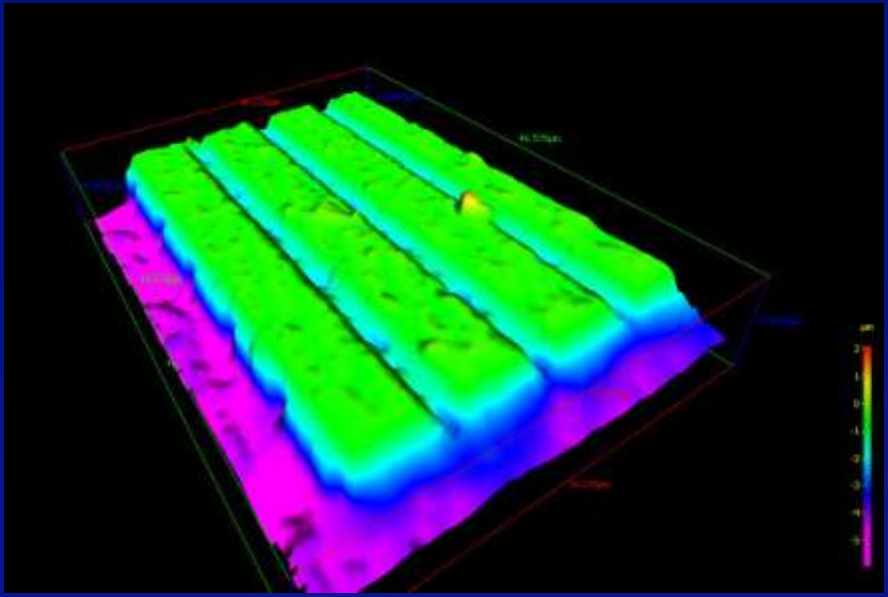


DEM

Image recognition software finds features, calculates elevation, forms digital model

A new approach:
Digital Elevation Models (DEM)

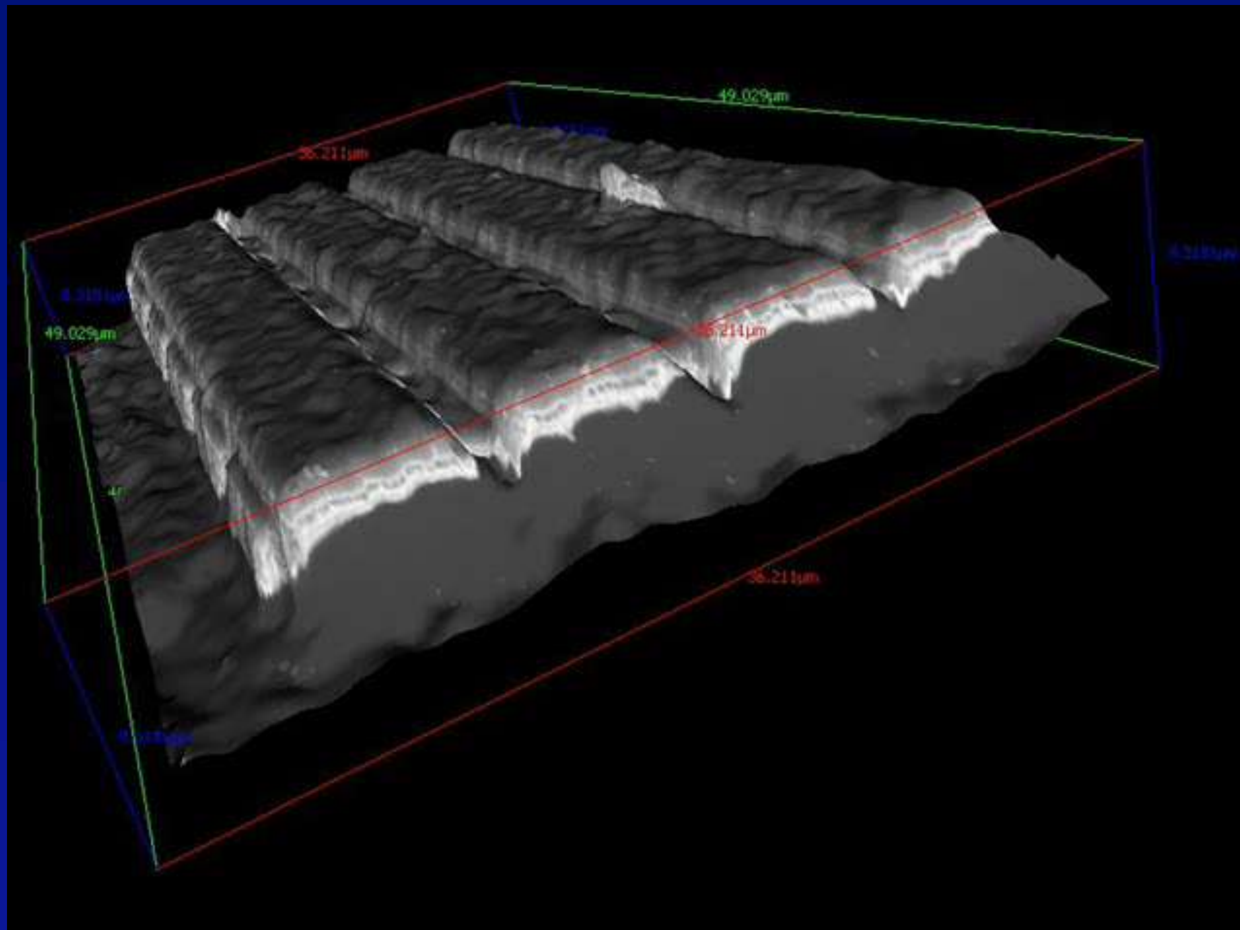




DEM with SEM contrast **DEM with color-height scale**

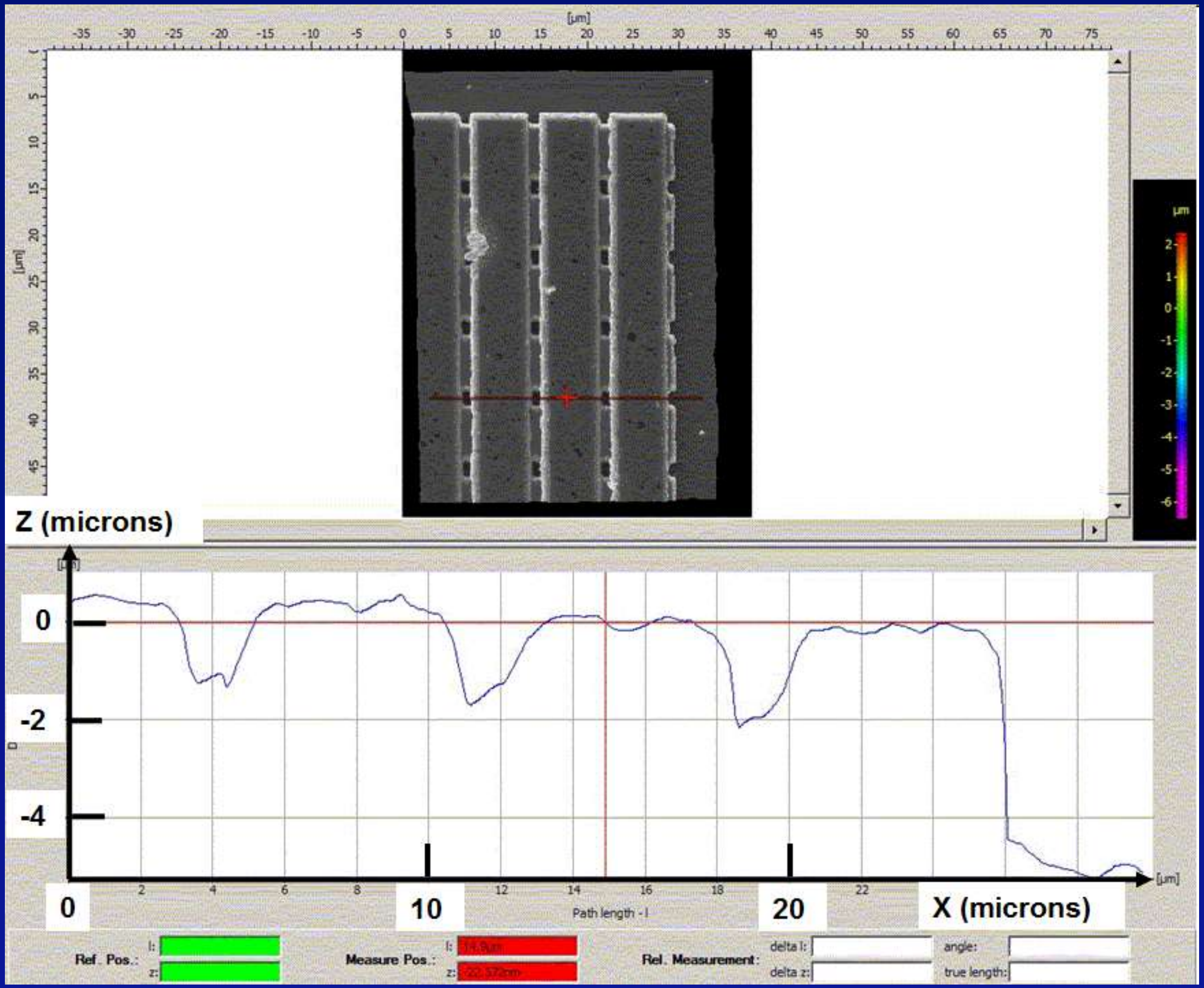
- **DEM with SEM contrast looks realistic**
- **DEM with color-height scale emphasizes topography**

A new approach:
Digital Elevation Models (DEM)



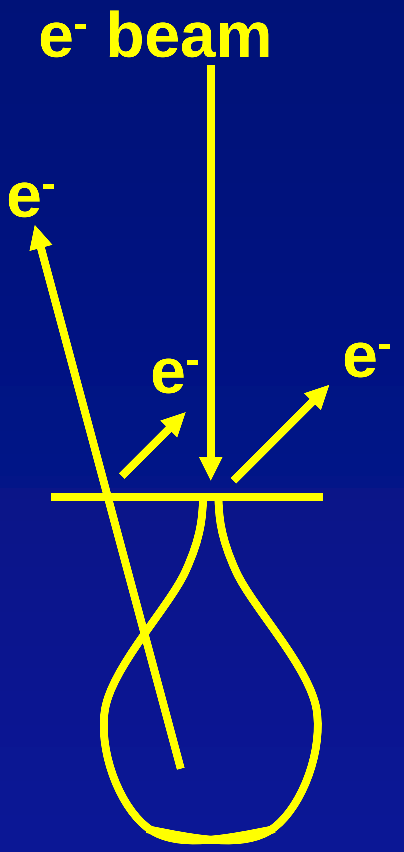
DEM requires about 1 minute to calculate
DEM can be manipulated in real time

Profile Analysis



Profile analysis provides artificial surface profile and rapid measurements in X and Z

Ultra-high Resolution SEM



Requirements for ultra-high resolution SEM:

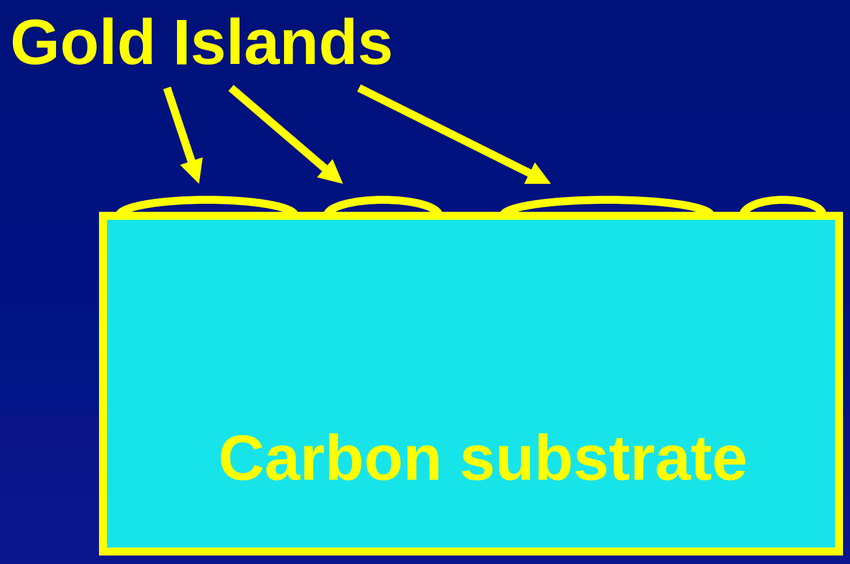
(1) An electron beam finely focused to a small spot at the sample surface.

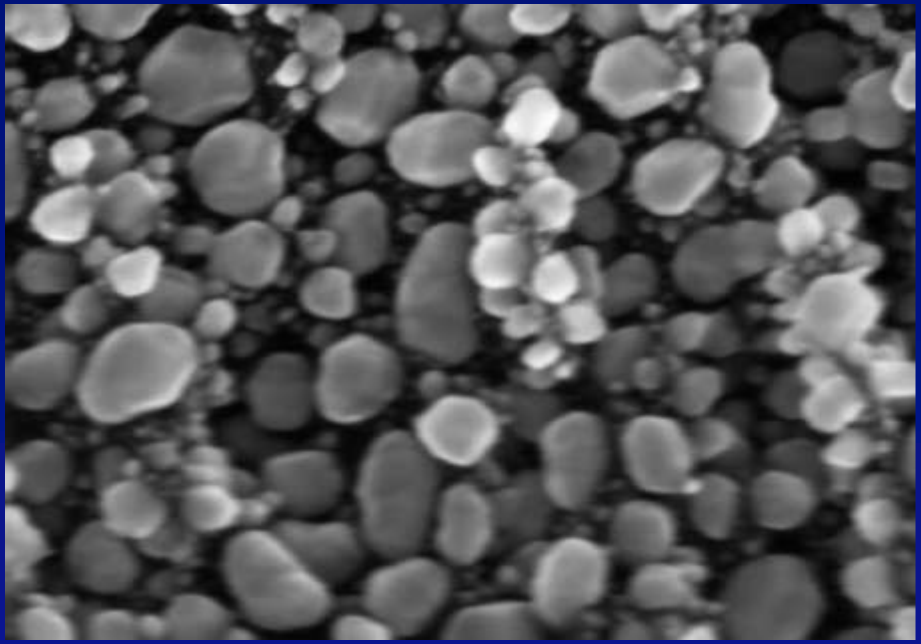
(2) Sufficient electron beam current to produce good image contrast.

(3) An imaging signal which originates very close to the electron beam impact site.

(1) and (2) generally require high electron beam voltage, which causes problems obtaining (3).

Gold-on-Carbon Resolution Sample



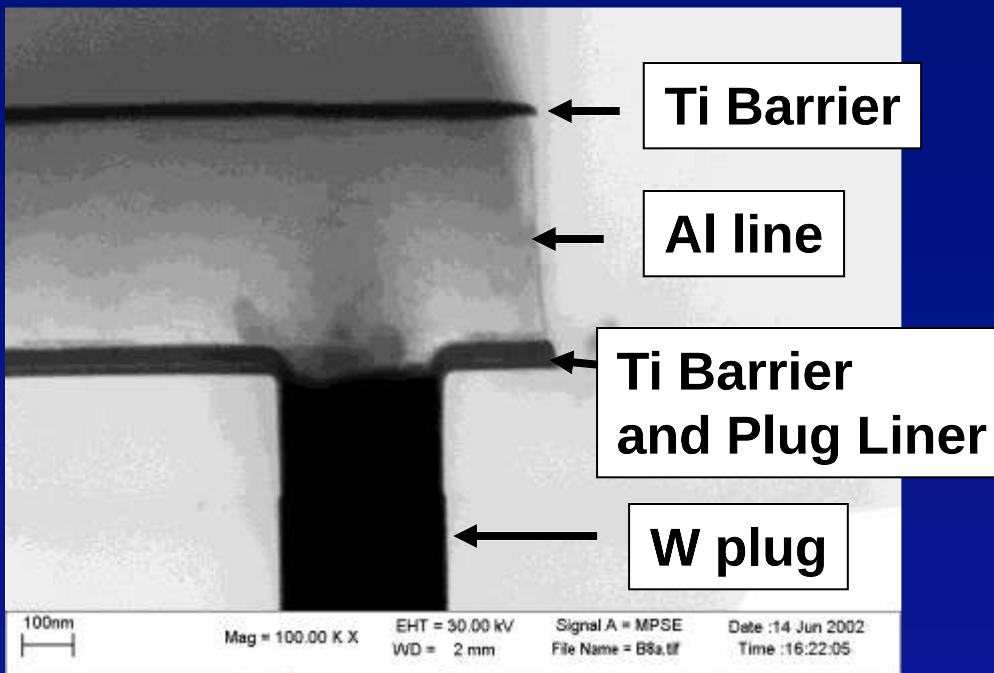


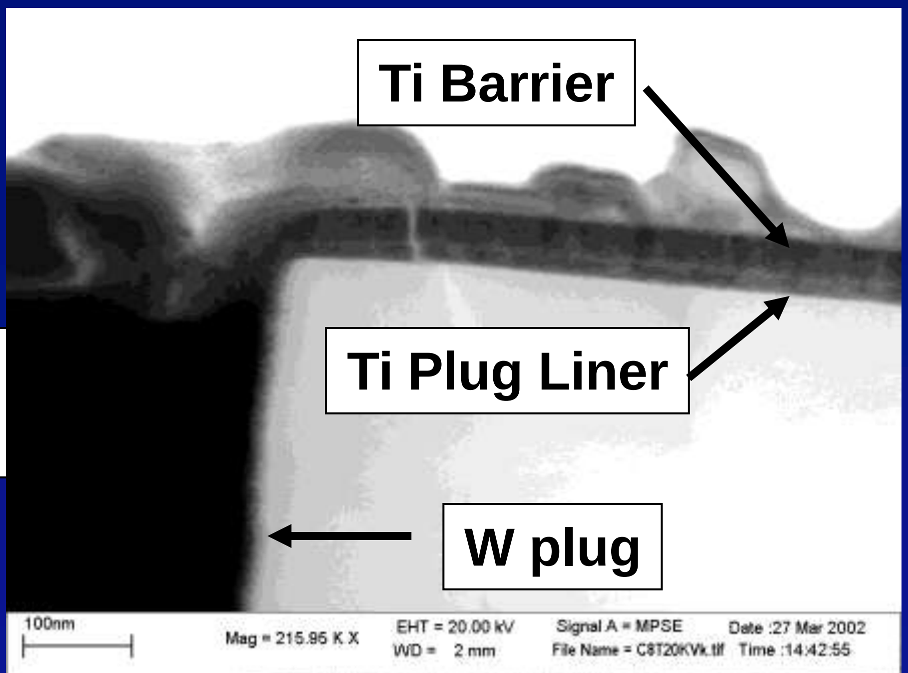
100 nm   **Mag = 500,000 x**

A highly reflective pattern (gold islands) on a strongly absorbing substrate (carbon) allows very high resolution imaging at high beam voltage.

STEM-in-SEM

STEM-in-SEM





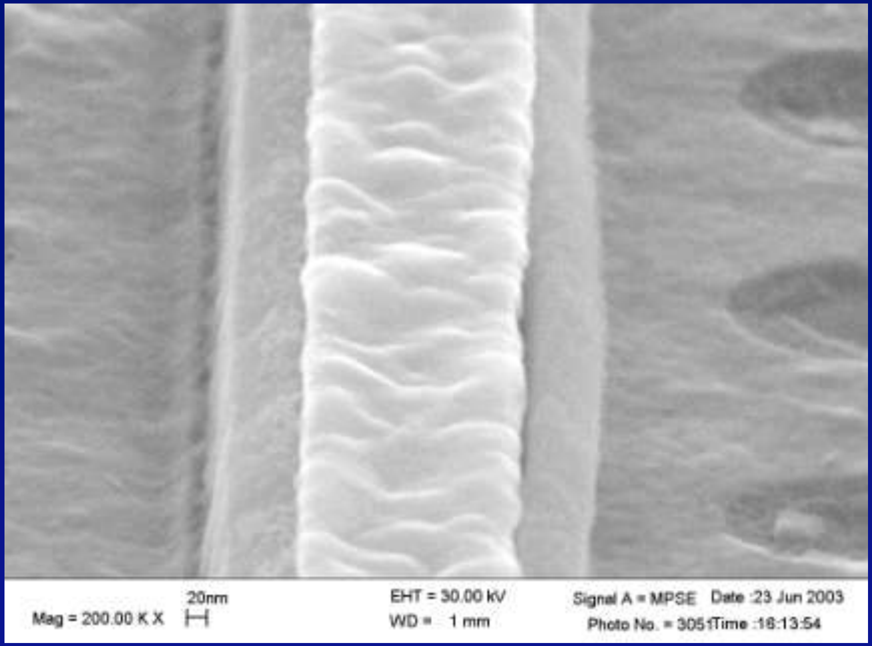
— 100 nm Mag = 100,000x

—— 100 nm Mag = 216,000x

High resolution is achieved on thin samples in the SEM using a specially designed sample holder.

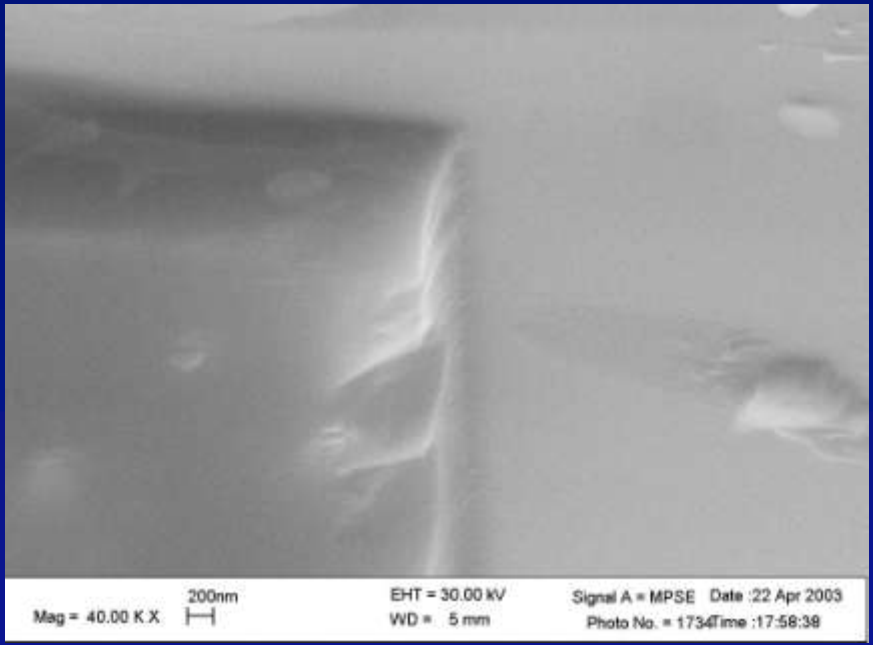
Forward scattered electron imaging

Uncoated poly-silicon



50 nm — Mag = 200,000 x

Uncoated photo-resist



0.5 μm — Mag = 40,000 x

High resolution is achieved on bulk samples in the SEM using a sample holder designed to collect 30 keV electrons forward scattered at a high incident angle. (W. Vanderlinde, ISTFA 2003)

Short Courses

- Lehigh Electron Microscopy School:

http://www.lehigh.edu/~inmatsci/shortcourses/Microscourses.html

- Maryland Practical Aspects of Electron Microscopy Short Course:

http://www.life.umd.edu/pasem/scanning.htm

- Pittcon Electron Microscopy and Microanalysis Short Course

http://www.micromaterialsresearch.com/Short%20Course.html

References

- Scanning Electron Microscopy and X-Ray Microanalysis : A Text for Biologists, Materials Scientists, and Geologists, by Joseph I. Goldstein, et al., 3rd Edition (2003).

- Scanning Electron Microscopy, X-ray Microanalysis, and Analytical Electron Microscopy: A Laboratory Workbook, by Charles E. Lyman, et al. (1990).

- "A review of wet etch formulations for silicon semiconductor failure analysis", by Thomas W. Lee, Microelectronics Failure Analysis Desk Reference, 4th Edition.

On the web

- http://www.microscopy-online.com/

Buyer's guides, lists of news groups and list servers.

- http://www.ou.edu/research/electron/www-vl/

Virtual Library of Microscopy. Thousands of links.

- http://micro.magnet.fsu.edu/

On-line virtual SEM. Also check out the "silicon zoo".

- http://mse.iastate.edu/microscopy/home.html

SEM tutorials and picture galleries.

- http://www.mos.org/sln/SEM/

Museum of Science – a very basic introduction to the SEM.

SEM Materials and Supplies

- Ernest F. Fullam, Inc.

http://www.fullam.com/

- Ted Pella, Inc.

http://www.tedpella.com/

- M.E. Taylor Engineering, Inc.

http://www.semsupplies.com/